
GEOLOGY
ARCHIBALD
GEIKIE

TEXT-BOOK OF GEOLOGY

BY

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PART THREE

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SCIENCE

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TEXT-BOOK OF GEOLOGY

BOOK IV

GEOTECTONIC (STRUCTURAL) GEOLOGY
(CONTINUED)

Section ii. Interbedded, Volcanic, or Contemporaneous Phase of Eruptivity

MASSES of igneous materials ejected to the surface in some of the forms now visible in modern volcanoes, possess great value as fixing the geological epoch of volcanic eruptions. It is evident that, on the whole, such superficial masses must agree in lithological characters with rocks already described, which have been extravasated by volcanic efforts without quite reaching the surface. Yet they have some well-marked general characters, of which the most important may be thus stated. (1) They occur as beds or sheets, sometimes lava-form, sometimes of fragmental materials, which conform to the bedding of the strata among which they are intercalated. (2) They do not break into or alter overlying strata. (3) The upper and under surfaces of the lava-beds present commonly a scoriaceous or vesicular character, which may even be found extending throughout the whole of a sheet. (4) Fragments of these upper surfaces not unusually occur in the immediately overlying strata. (5) Beds of tuff are frequently interstratified with sheets of lava, but may also occur by themselves, interstratified among ordinary sedimentary strata.

§ 1. Crystalline, or Lavas

While the underground course of a protruded mass of molten igneous rock has widely varied according to the shape of the channel through which it proceeded and in which, as in a mold, it solidified, the behavior of the rock, once poured out at the surface, has been much more uniform. As in modern lava, the erupted mass has rolled along, varying in thickness and other minor characters, but retaining the broad general aspect of a lenticular bed or sheet. A comparison of such a bed with one of the intrusive sheets already described shows that in several important lithological characters they differ from each other. An intrusive sheet is closest in grain near its upper and under surfaces. A contemporaneous bed or true lava-flow, on the contrary, is there usually most open and scoriaceous. In the one case, we rarely see vesicles or amygdales, in the other they often abound. However rough the upper surface of an interbedded sheet may be, it never sends out veins into, nor incloses portions of, the superincumbent rocks, which, however, sometimes contain portions of it, and wrap round its hummocky irregularities. Occasionally it may be observed to be full of rents, which have been filled up with sandstone or other sedimentary material. These rents were formed while the lava was cooling, and sand was subsequently washed into them. Examples of this structure abound among the porphyrites of the volcanic tracts of the Scottish Lower Old Red Sandstone. The amygdaloidal cavities throughout an interbedded sheet, but more especially at the top, often present an elongated form, and are even pulled out into tube-like hollows in one general direction, which was obviously the line of movement of the

yet viscous mass (pp. 181, 388). Some kinds of rock, when occurring in interbedded sheets, are apt to assume a system of columnar jointing. Basalt, in particular, is distinguished by the frequency and perfection of its columns. The Giants' Causeway, the cliffs of Staffa, of Ardtun in Mull, and of Loch Staffin in Skye, the Orgues d'Expailly in Auvergne, and the Kirschberg of Fulda are well-known examples.

Interbedded lavas of former geological periods, like those

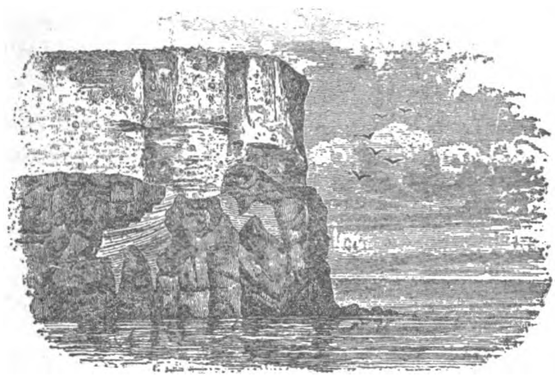

Fig. 302.—Sandstone filling rents in the surface of an interbedded sheet or flow of porphyrite, which is covered with a bed of conglomerate. Coast of Kincardineshire.

The rents have been filled in with sand before the eruption of the next flow.

of recent date (ante, p. 408), occur under two tolerably well-defined conditions.

1. Lenticular sheets or groups of sheets, usually of limited extent and with associated bands of tuff, form the more frequent type among Palæozoic and Secondary formations. A single interbedded sheet may occasionally be found intercalated between ordinary sedimentary strata, without any other volcanic accompaniment. But this is unusual. In the great majority of cases, several sheets occur together, with accompanying bands of contemporaneous tuff.

In such abundantly volcanic districts as central Scotland, the necks or vents of eruption (p. 969) may frequently be detected around the lavas which proceeded from them. The thickness of an interbedded sheet varies for different kinds of lava. As a rule, the more acid rocks are in thicker beds than the more basic. Some of the thinnest and most persistent sheets may be observed among the basalts, where a thickness of not more than 12 or 15 feet for each sheet is not uncommon. Both individual sheets and groups of sheets possess a markedly lenticular character. They may be seen to thicken in a particular direction, probably that from which they flowed. Thus in Linlithgowshire a mass of lavas and tuffs, reaching a collective thickness of probably 2000 feet in the Carboniferous Limestone series, rapidly dies out, until within a distance of only ten miles it dwindles down to a single band less than fifty feet thick. On the other hand, beds of tolerably uniform thickness and flatness of surface may be found; among the basalts, more particularly, the same sheet may be traceable for miles, with re-

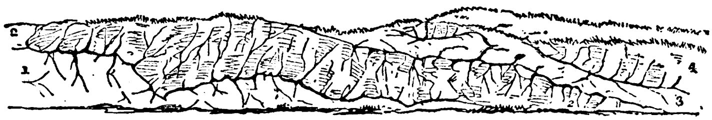

Fig. 303.—Four successive flows of porphyrite, Lower Carboniferous, East Linton.

markable regularity of thickness and parallelism between its upper and under surfaces (p. 385). The porphyrites (Fig. 303) and trachytic and felsitic lavas are more irregular in thickness and form of surface (p. 378).

Abundant examples of this type of volcanic extrusion may be studied among the Palæozoic and Tertiary formations of Western Europe, and nowhere on a larger scale than in the British Isles. The Cambrian lavas and tuffs of Pembrokeshire, and those of Arenig and Bala age in North Wales, the Lake District, the south of Scotland, and the southeast of Ireland, form a notable record of volcanic activity in older Palæozoic time. They were succeeded by the great outpourings of the Old Red Sandstone, Devonian, Carboniferous, and Permian volcanoes. But the volcanic energy gradually diminished until the last Carboniferous and Permian eruptions gave rise to *puys* like those of Auvergne, never discharging such voluminous floods of lava as those of earlier periods, and probably in many

cases emitting only showers of ashes and stones.[1] There appears to have been a complete quiescence of volcanic activity during the whole of the Mesozoic ages in Britain. But the subterranean fires were rekindled in older Tertiary time, and gave forth the great basalt sheets of Antrim and the Inner Hebrides.

On the continent of Europe a similar long record of volcanic action is found, with a corresponding Mesozoic quiescence. Cambrian, Silurian, Devonian, Carboniferous, and Permian volcanic rocks have been found in France. The Permian volcanic rocks of Germany have long been well known.[2] In the Tyrol extensive sheets of quartz-porphyry of Triassic or older date with associated tuffs occur.[3]

Interbedded (and also intrusive) sheets have shared in all the subsequent curvature and faulting of the formations among which they lie. This relation is well seen in the "toadstone" or diabase beds associated with the Carboniferous Limestone of Derbyshire (Fig. 304).[4]

Fig. 304.—Section of intercalated diabase (toadstone) in Carboniferous Limestone, Derbyshire (*B.*). *a a*, Toadstone, in two beds; *b b*, Limestones; *c*, Millstone grit; *f f*, Faults.

2. The second type is displayed in widespread plateaus composed of many successive sheets, frequently with little or no intercalation of tuff. It occurs even among Palæozoic formations, but attains its greatest development among the volcanic eruptions of Tertiary time. Instead of mere local lenticular patches, these sheets lie piled over each other sometimes to a depth of several thousand feet, and frequently cover areas of many thousand square miles.

[1] Quart. Journ. Geol. Soc. (Anniv. Address), vol. xlviii. p. 147.
[2] References to the intercalated volcanic rocks of former geological periods will be found in the account of the geological systems in Book VI.
[3] E. Mojsisovics, "Die Dolomit-riffe von Südtirol," 1879.
[4] See Section 18, "Hor. Sec. Geol. Surv. Great Britain."

Among the Palæozoic rocks of Scotland remnants of such ancient volcanic plateaus occur in the Old Red Sandstone (hills of Lorne) and Carboniferous systems (Campsie Fells and hills above Largs), where they consist chiefly of consecutive sheets of different porphyrites and diabases rising into long terraced table-lands. The regularity of thickness and parallelism of these sheets form conspicuous features in the scenery of the districts in which they occur.

It is chiefly basaltic rocks, however, that in all parts of the world have flowed out without the production of prominent cones and craters, and now build up vast volcanic plateaus. The fragmentary Miocene plateaus of the British Islands, the Faroe Islands and Iceland; those of the Indian Deccan and of Abyssinia, and the more recent basalt floods which have closed the eventful history of volcanic action in North America, are notable illustrations of this type of structure. Beds of tuff, conglomerate, gravel, clay, shale, or other stratified intercalations occasionally separate the sheets of basalt. Layers of lacustrine clays, sometimes full of leaves, and even with sufficiently thick masses of vegetation to form bands of lignite or coal, may also here and there be detected. But marine intercalations are rare or absent. There can be no doubt that these widely extended sheets of basalt were in the main subaerial outpourings, and that in the hollows of their hardened surfaces lay lakes and smaller pools of water in which the interstratified sedimentary materials were laid down. The singular persistence of the basalt-beds has often been noticed. The same sheet may be followed for several miles along the magnificent cliffs of Skye and Mull. Mr. Clarence King believes that single sheets of basalt in the Snake River lava-field of Idaho may have flowed for 50 or 60 miles.[5] The basalts, however, so exactly resemble each other that the eye may be deceived unless it can follow a band without any interruption of continuity.

§ 2. Fragmental, or Tuffs

While the observer may be in doubt whether a particular bed of lava has been poured out at the surface as a true flow, or has consolidated at some depth, and, there-

[5] "Geological Exploration of 40th Parallel," i. p. 593. See also C. E. Dutton, Nature, 27th November, 1884. 6th Ann. Rep. U. S. Geol. Surv. 1884–85, p. 181, and 4th Ann. Rep. of same Survey, 1882–83, p. 85.

fore, whether or not it is to be regarded as evidence of an actual volcanic outbreak at the locality, he is not liable to the same uncertainty among the fragmental eruptive rocks. Putting aside the occasional brecciated structure seen along the edges of plutonic intrusive masses, he may regard all the truly fragmental igneous rocks as proofs of volcanic action having been manifested at the surface. The agglomerate found in a volcanic neck could not have been formed unless the vapors in the vent had been able to find their way to the surface, and in so doing to blow into fragments the rocks on the site of the vent as well as the upper part of the ascending lava-column.[6] Wherever, therefore, a bed or a series of beds of tuff occurs interstratified in a geological formation, it points to contemporaneous volcanic eruptions. Hence the value of these rocks in interpreting the volcanic annals of a region.

The fragmentary ejections from a volcano or a cooling lava-stream vary from the coarsest agglomerate to the finest tuff, the coarser materials being commonly found nearest to the source of discharge. They differ in composition, according to the nature of the lavas with which they are associated and from which they have been derived. Thus, a region of trachyte-lavas supplies trachyte-tuffs and trachyte-breccias; one of basalts gives basalt-breccias, basalt-agglomerates, basalt-tuffs; one of obsidians yields pumiceous tuffs and breccias. The fragmentary matter ejected from volcanic vents has fallen partly back into the funnels of discharge, partly over the surrounding area. It is apt, therefore, to be more or less mingled with

[6] It is conceivable that where a mass of lava was injected into a subterranean cavern, fragmentary discharges might take place and partly fill that cavity; but such exceptional cases are probably extremely rare.

ordinary sedimentary detritus. We find it, indeed, passing insensibly into sandstone, shale, limestone, and other strata. Alternations of gravelly *peperino*-like tuff with a very fine-grained "ash" may frequently be observed. Large blocks of lava-form rock, as well as of the strata through which the volcanic explosions have taken place, occur in the tuffs of most old volcanic districts. Occasionally such ejected blocks or bombs are found among fine shales and other strata, the lamination of which is bent down round them

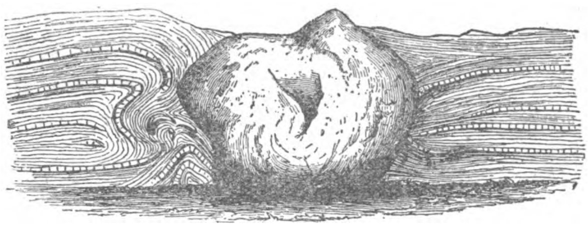

Fig. 305.—Ejected volcanic block (12 by 15 by 17 inches) in Lower Carboniferous Shales, Pettycur, Fife.

in such a way as to show that the stones fell with considerable force into the still soft and yielding silt or clay (Fig. 305).[7]

Volcanic tuffs and conglomerates occur in interstratified beds without any accompanying lava, much more commonly than do interstratified sheets of lava, without beds of tuff; just as, in recent volcanic districts, it is more usual to find cones of ashes or cinders without lava, than lava-sheets without an accompaniment of ashes. Masses of fine or gravelly tuff, several hundreds of feet in thickness, without the intervention of any lava-bed, may be observed in the volcanic districts of the Old Red Sandstone and Carboniferous systems in Scotland. These furnish evidence of long-continued volcanic action, during which

[7] See Geol. Mag. i. 1864, p. 22.

fragmentary materials were showered out over the water-basins, mingled with little or no ordinary sediment. On the other hand, in these same areas, thin seams of tuff interlaminated with sandstone, shale, or limestone, afford indications of feeble intermittent volcanic explosions, whereby light showers of dust were discharged, which settled down quietly amid the sand, mud, or limestone accumulating at the time. Under these latter circumstances, tuffs often become fossiliferous; they inclose the remains of such plants and animals as might be lying on the lake-bottom or sea-floor over which the showers of volcanic dust fell, and thus they form a connecting link between aqueous and igneous rocks.

As illustrations of the nature of the stratigraphical evidence for former conditions of volcanic activity, two sections from Linlithgowshire may here be given. In the first of these (Fig. 306), a black shale (1) of the usual carbonaceous type, with remains of terrestrial plants, lies at the bottom. It is covered by a bed of nodular bluish-gray tuff (2), containing black shale fragments, whence we may infer that the underlying or some similar shale was blown out from the site of the vent that furnished this dust and gravel. A second black shale (3) is succeeded by a second thin band of fine pale yellowish tuff (4). Black shale (5) again supervenes, containing rounded fragments of tuff, perhaps lapilli intermittently ejected from the neighboring vent, and passing up into a layer of tuff (6), which marks how the volcanic activity gradually increased again. It is evident that, but for the proximity of an active volcanic vent, there would have been a continuous deposit of black shale, the conditions of sedimentation having remained unchanged. In the next stratum of shale (7), thin seams and nodules of clay-ironstone accumulated round decomposing

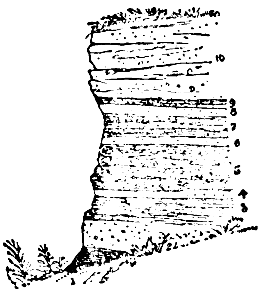

Fig. 306. — Section of interstratifications of tuff and shale, Old Quarry, Wester Ochiltree, Linlithgowshire (Lower Carboniferous).

organic remains on the muddy bottom. A brief volcanic explosion is marked by the thin tuff-bed (8), after which the old conditions of deposit continued, the bottom of the water, as the shale (9) shows, being crowded with ostracod crustaceans, while fishes, whose coprolites have been left in the mud, haunted the locality. At last, however, a much more powerful and prolonged volcanic explosion took place. A coarse agglomerate or tuff (10), with blocks sometimes nearly a foot in diameter, was then thrown out and overspread the lagoon.

The second example (Fig. 307) brings before the mind a volcanic episode of another kind, in the history of the same region. At the bottom of the section, a pale amygdaloidal, somewhat altered form of basalt (A) marks the upper surface of one of the submarine lavas of the Carboniferous Limestone period. Directly over it comes a bed of limestone (B) 15 feet thick, the lower layers of which are made up of a dense growth of the thin-stemmed coral, *Lithostrotion irregulare*, which overspread the hardened lava. The next stratum is a band of dark shale (C), about 2 feet thick, followed by about the same thickness of an impure limestone with shale seams. The conditions for coral growth were evidently not favorable; for the deposit of this argillaceous limestone was arrested by the precipitation of a dark mud, now to be seen in the form of 3 or 4 inches of a black pyritous shale (E), and next by the inroad of a large quantity of a dark sandy mud, and drift vegetation, which has been preserved as a sandy shale (F) containing *Calamites*, *Producti*, ganoid scales, and other traces of the terrestrial and marine life of the time. Finally a sheet of lava, represented by the uppermost amygdaloid (G), overspread the area, and sealed up these records of Palæozoic history.[8]

Fig. 307.—Section in Wardlaw Quarry, Linlithgowshire.

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[8] See "Memoirs of Geol. Survey, Geology of Edinburgh," pp. 45, 58. Trans. Roy. Soc. Edin. xxix. p. 483.

PART VIII. METAMORPHISM, LOCAL AND REGIONAL

At the outset some caution must be employed as to the use of the terms "metamorphism" and "metamorphic." It is obvious that we have no right to call a rock metamorphic, unless we can distinctly trace it into an unaltered condition, or can show from its internal composition and structure that it has undergone a definite change, or can prove its identity with some other rock whose metamorphic character has been satisfactorily established. Further, it must be remembered that, in a certain sense, all or nearly all rocks may be said to have been metamorphosed, since it is exceptional to find any, not of very modern date, which do not show, when closely examined, proofs of having been hardened by the pressure of superincumbent rock, and altered by the action of percolating water or other daily acting agent of change. Even a solid crystalline mass, which, when viewed on a fresh fracture with a good lens, seems to consist of unchanged crystalline particles, will often betray under the microscope unmistakable evidence of alteration. And this alteration may go on until the whole internal organization of the rock, so far at least as we can penetrate into it, has been readjusted, though the external form may still remain such as hardly to indicate the change, or to suggest that any new name should be given to the recomposed rock. Among many igneous rocks, particularly the more basic kinds (diabases, basalts, andesites, diorites, olivine rocks, etc.), alteration of this nature may be studied in all stages.[1]

But mere alteration by decay is not what geologists de-

[1] See Index, sub voce, "Weathering."

note by metamorphism. The term has been, indeed, much too loosely employed: but it is now generally used to express a change in the mineralogical or chemical composition and in the internal structure of rocks, produced at some depth from the surface, through the operation of mechanical movement, combined with the influence of heat and heated water or vapor. A metamorphic rock may be more compact and crystalline than the parent mass from which it has been derived, like which, also, when exposed at the surface, it again undergoes alteration by weathering.

Various kinds of metamorphism have been distinguished by special names;[2] but they may be included in three main groups. 1st, change of texture, including the induration and other minor phenomena of "contact-metamorphism"; 2d, change of form, including all paramorphic transformations, such as the conversion of a pyroxenic into a hornblendic rock, and the alteration of a clastic into a crystalline mass by the crystallization of its original constituents; 3d, change of substance, where a chemical change has been superinduced either by the abstraction or addition of one

[2] For instance, metasomatosis, metasomatic, methylosis, methylotic, and metachemic applied to chemical metamorphism or alteration of constitution or substance; metastasis, indicating changes of a paramorphic nature; metacrasis, denoting such transformations as the conversion of mud into a mass of mica, quartz and other silicates; macro-structural metamorphism, having the external structure (morphology) changed, as where an amorphous condition becomes schistose; micro-structural, having the internal structure (histology) wholly changed, with or without a macro-structural alteration; mineralogical, having one or more of the component minerals changed, with or without an alteration of the chemical composition of the rock as a whole. See King and Rowney, "An old Chapter of the Geological Record," 1881; Dana, Amer. Journ. Sci. xxxii. 1886, p. 69. Bonney, Quart. Journ. Geol. Soc. 1886, Address, p. 30 *et seq.* G. H. Williams, Bull. U. S. Geol. Surv. No. 62, 1890, p. 43. Various terms have likewise been proposed for metamorphism from the point of view of its cause, as Dislocation-metamorphism (Lossen), Mechanical metamorphism (Heim and Baltzer), Dynamical metamorphism (Rosenbusch), Heaping-up metamorphism (Stauungs M., Credner), Pressure metamorphism (Bonney).

or more ingredients, as in the remarkable contact zones round certain intrusive bosses. It is obvious, however, that each of these three kinds of metamorphism may be included in the changes which have been superinduced upon a given mass of rock.

The conditions that appear to be mainly concerned in metamorphism have been already stated (p. 542). It may be added here that these conditions may in different cases be supplied: 1st, by the action of heated subterranean water carrying carbonic acid and mineral solutions (p. 519); 2d, by the action of hot vapors and gases upon underground rocks (pp. 388, 518, 977); 3d, by mechanical movements, particularly those which have resulted in the crushing and shearing of rocks (p. 529); 4th, by the intrusion of heated eruptive rocks, sometimes containing a large proportion of absorbed water, vapors, or gases (pp. 392, 944, 950, 957); 5th, occasionally and very locally by the combustion of beds of coal.

When the term "metamorphism" was originally proposed by Lyell it applied to rocks having a schistose or foliated structure which were regarded as altered sediments. For many years afterward it continued to be used in the same sense, and not until comparatively recently did geologists recognize that rocks originally of eruptive origin but interposed among sedimentary strata were necessarily affected by the changes which the latter underwent in the processes of metamorphism. It is now well established that igneous rocks no less than aqueous have been metamorphosed, and, as Lossen has pointed out, they furnish in some respects even a better starting-point from which to attack the problem of metamorphism, inasmuch as their original definite mineral aggregation, chemical composition,

and structure furnish a scale by which the subsequent mutations of the rocks may be traced and measured.[3]

Metamorphism is manifested in two distinct phases. 1st, Local (the metamorphism of contact or of juxtaposition), where the change has been effected only within a limited area, round some eruptive mass, beyond which the ordinary condition of the altered rocks can be seen. 2d, Regional, where the change has taken place over a large tract without reference to visible eruptive masses, the original characters of the altered rocks being more or less completely effaced. Between the results of local and regional metamorphism, no sharp line can be drawn; they insensibly graduate into each other and may arise from one common cause.

§ i. Local Metamorphism (metamorphism of contact or juxtaposition)

In this kind of alteration two fundamental conditions have to be considered: 1st, the nature, mass, temperature, and composition of the eruptive rock; and, 2d, the composition and structure of the rocks through which the intrusive material has been injected. With regard to the first of these conditions, it is obvious that a large intrusion will produce more alteration than a small intrusion of the same rock. The areole of metamorphism round a great boss of granite or of diorite will be broader and the metamorphism itself more intense than round a mere vein or dike. But the case is different when we compare intrusions of altogether unlike materials. The temperature of granite appears to have been comparatively low (p. 524). We never meet with cases of

[3] Jahrb. Preuss. Geol. Landesanst. 1884, p. 620. See also, for an early study of the influence of contact-metamorphism on augitic igneous rocks Allport, Q. J. Geol. Soc. xxxii. 1876, p. 418.

fusion round even the largest bosses of granite; carbonate of lime is not deprived of its carbonic acid. But the injections of intermediate and basic rocks give proofs of far more elevated temperatures. Dikes of andesite or basalt may often be observed to have baked argillaceous rocks into porcellanite, and to have actually fused the rocks in contact with them. But in these instances the alteration is confined within limits of a few inches or feet. The metamorphism induced round a boss of granite, on the other hand, may extend for a breadth of a mile or more. Much of the change in the latter case may be ascribed to the influence of the mineralizing agents with which the granite was impregnated (see p. 523).

With respect to the influence of the nature and structure of the altered rock upon the metamorphism, it is obvious that such different materials as shale, sandstone, coal, and limestone will give very different results even if exposed to the same amount and kind of metamorphic energy. And much will depend also upon the relation between the position of the intrusive mass and the stratification of the rocks affected. As stated on p. 98, heat is conducted four times faster along the planes of stratification than across the bedding.

The following examples of the nature of the metamorphism of contact are arranged in progressive order of intensity, beginning with the feeblest change, and ending with results that are quite comparable with the great changes involved in regional metamorphism.

Bleaching is well seen at the surface, where heated volcanic vapors rise through tuffs or lavas and convert them into white clays (p. 398). Decoloration, however, has proceeded also, underneath, along the sides of dikes. Thus in

Arran, a zone of decoloration ranging from 5 or 6 to 25 or 30 feet in width, runs in the red sandstone along each side of many of the abundant basalt-dikes. This removal of the coloring peroxide may have been effected by the prolonged escape of hot vapors from the cooling lava of the dikes. Had it been due merely to the reducing effect of organic matter in the meteoric water filtering down each side of the dike, it ought to occur as frequently along joints in which there has been no ascent of igneous matter.

Coloration.—Rocks, particularly shale and sandstone, in contact with intrusive sheets, are sometimes so reddened as to resemble the burned shale from an ironwork. Every case of reddening along a line of junction between an eruptive and non-eruptive rock must not, however, be set down without examination as an effect of the mere heat of the injected mass, for sometimes the coloring may be due to subsequent oxidation of iron in one or both of the rocks by water percolating along the lines of contact.

Induration.—One of the most common changes superinduced upon sedimentary rocks along their contact with intrusive masses, is a hardening of their substance. Sandstone, for example, is converted into a compact rock which breaks with the lustrous fracture of quartzite. Argillaceous strata are altered into flinty slate, Lydian-stone, jasper, or porcellanite. This change may sometimes be produced by mere dry heat, as when clay is baked. But probably, in the majority of cases, induration of subterranean rocks results from the action of heated water. The most obvious examples of this action are those wherein the percentage of silica has been increased by the deposit of a siliceous cement in the interstices of the stone, or by the replacement of some of the mineral substances by silica. This

is specially observable round eruptive masses of granite and diabase.[4]

Expulsion of Water.—One effect of the intrusion of molten matter among the ordinary cool rocks of the earth's crust has doubtless often been temporarily to expel their interstitial water. The heat may even have been occasionally sufficient to drive off water of crystallization or of chemical combination. Mr. Sorby mentions that it has been able to dispel the water present in the minute fluid cavities of quartz in a sandstone invaded by diabase.[5]

Prismatic Structure.—Contact with eruptive rocks has frequently produced a prismatic structure in the contiguous

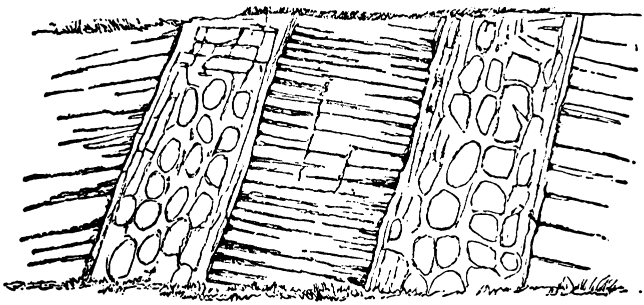

Fig. 308.—Sandstone (*a a*) rendered prismatic by Dolerite (*b b*); Bishopbriggs, Glasgow.

masses. Conspicuous illustrations of this change are displayed in sandstones through which dikes have risen (Fig. 308). Independently of the lines of stratification, polygonal prisms, six inches or more in diameter, and several feet in length, starting from the face of the dike, have been developed in the sandstone.[6]

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[4] Kayser, on contact-metamorphism around the diabase of the Harz, Z. Deutsch. Geol. Ges. xxii. 103, where analyses showing the high percentage of silica are given. Hawes, Amer. Journ. Sci. January, 1881. The phenomena of metamorphism round granite are further described below, p. 1003 *et seq.*

[5] Q. J. Geol. Soc. 1880. Ante, p. 954.

[6] Sandstone altered by basalt, melaphyre, or allied rock, Wildenstein, near

Some of the most perfect examples of superinduced prisms may occasionally be noticed in seams of coal which have been invaded by intrusive igneous rocks. In the Scottish coal-fields, sheets of basalt have been forced along the surfaces of coal-seams, and even along their centre, so as to form a bed or sheet in the middle of the coal-seam. The coal in these cases is sometimes beautifully columnar, its slender hexagonal and pentagonal prisms, like rows of stout pencils, diverging from the surface of the intrusive sheet.[7]

Other examples of the production of this structure have been described in dolomite altered by quartz-porphyry (Campiglia, Tuscany); fresh-water limestone altered by basalt (Gergovia, Auvergne); basalt-tuff and granite altered by basalt[8] (Mt. Saint-Michel, Le Puy).

Calcination, Melting, Coking.[9]—By the great heat of erupted masses, more especially of basalt and its allies, rocks have been calcined and partially or completely melted. In some, the matrix or some of the component minerals have been melted; in others, the whole rock has been fused Among granite fragments ejected with the slags of old volcanic vents in Auvergne, some present no trace of alteration, others are burned as if they had been in a furnace, or are partially melted so as to look like slags, each of their component minerals, however, remaining distinct. In the

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Büdingen, Upper Hesse, Schöberle, near Kriebitz, Bohemia; Johnsdorf, near Zittau, Saxony (the Quader-sandstone of Gorischstein, in Saxon Switzerland, is beautifully columnar; W. Keeping, Geol. Mag. 1879, p. 437); Bishopbriggs, near Glasgow.

[7] Coal and lignite, with their accompanying clays, altered by basalt, diabase, melaphyre, etc., Ayrshire, Scotland; St. Saturnin, Auvergne; Meissner, Hesse Cassel; Ettingshausen, Vogelsgebirge; Sulzbach, Upper Palatinate of Bavaria; Fünfkirchen, Hungary: by trachyte, Commentry, Central France; by phonolite, Northern Bavaria.

[8] Naumann, "Geognosie," i. p. 737.

[9] It is worthy of observation that changes of the kind here referred to occur most commonly with basalt-rocks, melaphyres and diabases. Trachyte has been a less frequent agent of alteration, though some remarkable examples of its influence have been noted. Poulett Scrope (Geol. Trans. 2d ser. ii.) describes the alteration of a trachyte conglomerate by trachyte into a vitreous mass. Quartz-porphyry and diorite occasionally present examples of calcination, or more or less complete fusion. But with the granitic and syenitic rocks changes of this kind have never been observed. Naumann, "Geognosie," i. p. 744.

Eifel volcanic region, the fragments of mica-schist and gneiss ejected with the volcanic detritus have sometimes a crust or glaze of glass. Sandstones, though most frequently baked into a compact quartzite, are sometimes changed into an enamel-like mass in which, when the rock contains an argillaceous or calcareous matrix with dispersed quartz-grains, the infusible quartz may be recognized (Oberellenbach, Lower Hesse). According to Bunsen's observations, volcanic tuff and phonolite have sometimes been melted for several feet on the sides of the dolerite dikes which traverse them, so as to present the aspect of pitchstone or obsidian.[10] Besides complete fusion and fluxion-structure there has sometimes been also a production of microscopic crystallites in the fused portions, resembling those of eruptive rocks.

The effects of eruptive rocks upon carbonaceous beds, and particularly upon coal-seams, are among the most conspicuous examples of this kind of alteration. In a coal-field much invaded by igneous rocks, seams of coal are usually found to have suffered more than the other strata, not merely because they are specially liable to alteration from the proximity of heated surfaces, but because they have presented lines of more easy escape for the igneous matter pressed from below. The molten rock has very generally been injected along the coal-seams; sometimes taking the lower, sometimes the upper surface, or even, as already stated, forcing its way along the centre.

The alterations produced by the intrusion vary considerably, according to the bulk and nature of the eruptive sheet,

[10] Usually the vitreous band at the margin of a basalt dike belongs to the intruded rock and not to that through which it has risen (see "Basalt-glass," ante, pp. 297, 969).

the thickness, composition, and structure of the coal-seam, and probably other causes. In some cases, the coal has been fused and has acquired a blistered or vesicular texture, the gas cavities being either empty or filled with some infiltrated mineral, especially calcite (east of Fife). In other examples, the coal has become a hard and brittle kind of anthracite or "blind coal," owing to the loss of its more volatile portions (west of Fife). This change may be observed in a coal-seam 6 or 8 feet thick, even at a distance of 50 yards from a large dike. Traced nearer to the eruptive mass, the coal passes into a kind of pyritous cinder, scarcely half the original thickness of the seam. At the actual contact with the dike, it becomes by degrees a kind of caked soot, not more perhaps than a few inches thick (South Staffordshire, Ayrshire). Coal altered into a prismatic substance has been above (p. 994) referred to; it has even been changed into graphite (New Cumnock, Ayrshire, see Fig. 301).

Striking as is the change produced by the intrusion of basalt into coals and bituminous shales, it is hardly more conspicuous than the alteration effected on the invading rock. A compact crystalline black heavy basalt or diabase, when it sends sheets and veins into a coal or highly carbonaceous shale, becomes yellow or white, earthy, and friable, loses weight, ceases to have any apparent crystalline texture, and, in short, passes into what would at first unhesitatingly be pronounced to be mere clay. It is only when the distinctly intrusive character of this substance is recognized in the veins and fingers which it sends out, and in its own irregular course in the altered coal, that its true nature is made evident. Microscopical examination shows that this "white-rock" or "white-trap" is merely an altered

form of some diabasic or basaltic rock, wherein the felspar crystals, though much decayed, can yet be traced, the augite, olivine, and magnetite being more or less completely changed into a mere pulverulent earthy substance.[11]

	I.	II.
Silica	38·830	36·8
Alumina	13·250	22·95
Lime	3·925	9·73
Magnesia	4·180	2·85
Soda	0·971	0·5
Potash	0·422	1·1
Iron protoxide	13·830	4·08 FeO
Iron peroxide	4·335	2·6 TiO_2
Carbonic acid	9·320	11·9
		0·75 P_2O_5
Water	11·010	7·7
	100·073	100·96

Traces of the glassy selvage of contact may still sometimes be detected in these altered rocks. The changes in the constitution of an igneous mass, owing to the surrounding rocks, is referred to at p. 948.

The basalt of Meissner (Lower Hesse) overlies a thick stratum of brown coal which shows an interesting series of alterations. Immediately under the igneous rock, a thin seam of impure earthy coal ("letten") appears as if completely burned. The next underlying stratum has been altered into metallic-lustred anthracite, passing downward into various black glossy coals, beneath which the brown coal is worthless. The depth to which the alteration extends is 5·3 metres.[12] Another example of alteration has been described by G. vom Rath from Fünfkirchen in Hungary.[13] A coal-seam has there been invaded by a basic

[11] The following analyses show the composition of these "white rock-traps." No. I., by Henry, is from the South Staffordshire coal-field ("The South Staffordshire Coal-Field," in Mem. Geol. Survey, p. 118); No. II., by E. Stecher, is from Newhalls, Queensferry, Linlithgowshire. (Tschermak's Mittheil. ix. 1887, p. 190. Proc. Roy. Soc. Edin. 1888, p. 172. These memoirs of Dr. Stecher give an account of the contact phenomena round the intrusive diabases of the Carboniferous series in the basin of the Firth of Forth.)

[12] Moesta, "Geologische Schilderung, Meissner und Hirschberge," Marburg, 1867.

[13] G. vom Rath, N. Jahrb. 1880, p. 276. In the above analysis the bitumen

igneous rock (perhaps diabase) now so decomposed that its true lithological character cannot be satisfactorily determined. Here and there, the intrusive rock lies concordantly with the stratification of the coal, in other places it sends out fingers, ramifies, abruptly ends off, or occurs in detached nodular fragments in the coal. The latter, in contact with the intrusive material, is converted into prismatic coke. The analysis of three specimens of the coal throws light on the nature of the change. One of these (A) shows the ordinary composition of the coal at a distance from the influence of the intrusive rock; the second (B), taken from a distance of about 0·3 metre (nearly 1 foot), exhibits a partial conversion into coke; while in the third (C), taken from immediate contact with the eruptive mass, nearly all the volatile hydrocarbons have been expelled.

	Ash	Sulphur	Coke	Bitumen
A.	8·29 per cent	2·074	79·7	20·3
B.	9·73 "	1·112	87·8	12·2
C.	45·96 "	0·151	95·3	4·7

During the subterranean distillation arising from the destruction or alteration of coal and bituminous shales, while the gases evolved find their way to the surface, the liquid products, on the other hand, are apt to collect in fissures and cavities. In central Scotland, where the coal-fields have been so abundantly pierced by igneous masses, petroleum and asphaltum are of frequent occurrence, sometimes in chinks and veins of sandstones and other sedimentary strata, sometimes in the cavities of the igneous rocks themselves. In West Lothian, intrusive sheets, traversing a group of strata containing seams of coal and oil-shale, have a distinctly bituminous odor when freshly broken, and little globules of petroleum may be detected in their cavities. In the same district, the joints and fissures of a massive sandstone are filled with solid brown asphalt, which the quarrymen manufacture into candles.

Marmarosis.—The conversion of ordinary dull granular limestone into crystalline or saccharoid marble may not infrequently be observed on a small scale, where an intrusive sheet or dike has invaded the rock. It is also observable

includes all volatile constituents driven off by heat, hence coke and bitumen = 100. Another instance is described by Gümbel from Mährisch-Ostrau, where coal is coked by an augite-porphyry, Verh. Geol. Reichsanst. 1874, p. 55.

as a general phenomenon, apart from the appearance of visible eruptive rocks, and in such cases serves to unite local and regional metamorphism. In zones of contact-metamorphism round granite and other eruptive bosses many minerals have crystallized out in the altered limestone, such as tremolite, zoisite, and garnet.

One of the earliest described examples of this change is that at Rathlin Island, off the north coast of Ireland (Fig. 309). Two basalt dikes (20 and 35 feet thick respectively) ascend there through chalk, of which a band 20 feet thick separates them. Down the middle of this central chalk band runs a tortuous dike one foot thick. The chalk between the dikes and for some distance on either side has been altered into a finely granular marble.[14] On the east side of the great intrusive mass of Fair Head the chalk is likewise marmarized. Another smaller but interesting illustration of the same change occurs at Camps Quarry near Edinburgh. The dull gray Burdie House limestone (Lower Carboniferous), full of valves of *Leperditia* and plants, has there been invaded by a basaltic dike, which, sending slender veins into the limestone, has inclosed portions of it. The limestone is found to have acquired the granular crystalline character of marble, each little granule of calcite having its own orientation of cleavage planes (Fig. 310).

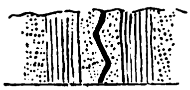

Fig. 309.—Dikes of basalt (*a a a*) traversing chalk (*b b*), which near the dikes is converted into marble (*c c*), Rathlin Island, Antrim.

Fig. 310.—Section of limestone (*a*) (Burdie House) converted into granular marble by basalt (*b*). Magnified 20 diameters.

Production of New Minerals.—One of the results of the intrusion of eruptive rock has been the development of

[14] Conybeare, Trans. Geol. Soc. iii. p. 210 and plate X. One of the most remarkable examples of marmarosis is the alteration of the (Triassic) limestone of Carrara into the well-known statuary marble (see Part VIII. "Summary").

crystalline minerals in ordinary sedimentary strata near the line of contact. The new minerals have usually an obvious affinity in composition with the original rock. But undoubtedly silica has often been introduced as part of the alteration, either free or as silicates. Moreover, a certain broad order of succession in the appearance of these new minerals may be observed in the larger areas of contact-metamorphism. On the outer margin of the ring or areole of metamorphism the internal rearrangements and mineralogical recombinations show themselves in many argillaceous rocks by the appearance of small knots or concretions which are replaced further inward by recognizable silicates, such as chiastolite, andalusite, staurolite, or kyanite, while toward the centre the dark mica which appears even in the outer parts of the ring attains a marked prominence, often accompanied with garnets and other new minerals.

A simple but interesting instance of this kind of contact-metamorphism was described many years ago by Henslow, near Plas Newydd, Anglesea. A basalt dike, 154 feet in breadth, there traverses strata of shale and argillaceous limestone, which are altered to a distance of 35 feet from the intrusive rocks, the limestone becoming granular and crystalline, and the shale being hardened, here and there porcellanized, while its shells (*Producti*, etc.), though nearly obliterated, are still traceable by their impressions. In the altered fossiliferous shale numerous crystals of analcime and garnet have been developed, the latter yielding as much as 20 per cent of lime.[15] Similar phenomena were observed by Sedgwick along the edges of intruded basalt among the Carboniferous limestones and shales of High Teesdale.[16]

In Hesse and Thuringerwald, Zirkel has described sandstones altered by contact with basalt, where the quartz-grains are enveloped in a vitreous matrix, in which abun-

[15] Cambridge Phil. Trans. i. p. 402.

[16] Op. cit. ii. p. 175.

dant microscopic microlites occur, and present in their arrangement evidence of a fluxion-structure. This glassy constituent probably represents the argillaceous and other materials in which the quartz-grains were originally imbedded, and which has been fused and made to flow by the heat of the basalt.[17]

Among localities where the development of new minerals in proximity to eruptive rock has taken place on the most extensive scale, none have been more frequently or carefully described than some in the group of mountains lying to the east and southeast of Botzen, in the Tyrol (Monzoni, Predazzo). Limestones of Lower Triassic (or Permian) age have there been invaded by masses of monzonite (a rock intermediate between syenite and diorite, sometimes containing much augite), granite, melaphyre, diabase, and orthoclase-porphyry. They have become coarsely-crystalline marble, portions of them being completely enveloped in the eruptive rock. But their most remarkable feature is that in them, and in the eruptive rocks in contact with them, many minerals often beautifully crystallized have been developed, including garnet, idocrase, gehlenite, fassaïte, pistacite, spinel, anorthite, mica, magnetic iron, hæmatite, apatite, and serpentine. Some of these minerals occur chiefly or only in the eruptive masses, others more frequently in the limestone, which is marked by a lime-silicate hornstone zone along the junction. But these are all products of contact of the two kinds of rock. Layers of carbonates (calcite, also with brucite) alternate with laminæ and streaks of various silicates, in a manner strikingly similar to the arrangement found in limestones among areas of regional metamorphism, where no visible intrusive rock has influenced the phenomena.[18]

Production of Foliation.—This is the most complete kind of metamorphic change, for not only are new minerals de-

[17] N. Jahrb. 1872, p. 7. For other examples see Mohl, Verhandl. Geol. Reichsanst. 171, p. 259; Hussak, Tschermak's Min. Mittheil. 1883, p. 530.

[18] On the Monzoni region, see Doelter, Jahrb. Geol. Reichsanstalt, 1875, p. 207, where a bibliography of the locality up to the date of publication will be found. Other papers have since appeared, of which the following dealing with the phenomena of contact-metamorphism may be mentioned. G. vom Rath, Z. Deutsch. Geol. Ges. 1875, p. 343; "Der Monzoni in südostlichen Tirol," Bonn, 1875; Lemberg, Z. Deutsch. Geol. Ges. 1877, p. 457.

veloped, but the whole texture and structure of the rock are altered. Reference has been already (p. 944 *et seq.*) made to the striking manner in which foliation has been superinduced upon ordinary sedimentary rocks round large bosses of granite. The details of this change deserve careful consideration, for they possess a high importance in relation to any theory of metamorphism.

In some cases (and probably these are more frequent than has been suspected) there has been a copious injection of granitic material not merely as large veins or dikes, but in minute threads and laminæ into the surrounding rock, following generally the more marked divisional planes, such as those of bedding, cleavage, or foliation. This impregnation or granitization has been strongly insisted upon by M. Michel-Lévy and has been noticed by other observers.[19] Near the contact of the micaceous schists of Saint Léon with the granite which pierces them, the distinguished French geologist found that the eruptive rock has been injected between the planes of the schists in leaves from a few millimetres to one or two centimetres thick, the rock has thus a ribboned appearance from the alternation of numerous dark micaceous layers with the finely granular pink or white veins from the granite. By such a process of metamorphism and injection sedimentary strata have acquired a structure that can hardly be distinguished from that of some ancient gneisses.[20]

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[19] Michel-Lévy, Bull. Soc. Geol. France, ix. 1881, p. 187; 1888, p. 221. Compt. Rend. International Geol. Congress, 1888. I have myself studied similar cases of injection among the schists around the granites near Lairg in Sutherland, and others have lately been worked out in detail by Messrs. Peach and Horne in the Geological Survey of the northeastern part of the same county.

[20] See Michel-Lévy "sur l'origine des Terrains crystallins primitifs," International Geol. Congress, 1888, p. 59; and the account of pre-Cambrian rocks, postea, Book VI.

Round the granite bosses of Devon and Cornwall, already referred to (ante, p. 946), the Devonian and Carboniferous formations have undergone remarkable changes, which have long been cited as classic examples of contact-metamorphism. Fine graywacke and slate have been converted into mica-schist and varieties of gneiss (cornubianite). In some cases the slates become indurated and dark in color, and new minerals (schorl, chiastolite, etc.) are developed in them. The volcanic bands intercalated with the sedimentary series likewise undergo alteration, the "greenstones," in particular, becoming much more coarsely crystalline as they approach the granite. Each boss of granite is surrounded with its ring of metamorphism, which varies greatly in breadth and in the intensity of alteration.[21]

In the Lake District of the north of England excellent examples of the phenomena of contact may be observed round the granite of Skiddaw. The alteration here extends for a distance of two or three miles from the central mass of granite. The slate, where unaltered, is a bluish-gray cleaved rock, weathering into small flakes and pencil-like fragments. Traced toward the granite, it first shows faint spots, which increase in number and size until they assume the form of chiastolite crystals, with which the slate is now abundantly crowded. The zone of this chiastolite-slate seldom exceeds a quarter of a mile in breadth. Still closer to the granite, a second stage of metamorphism is marked by the development of a general schistose character, the rock becoming more massive and less cleaved, the cleavage-planes being replaced by an incipient foliation due to the development of abundant dark little rectangular or oblong spots, probably imperfectly crystallized chiastolite, this mineral, as well as andalusite, occurring also in large crystals, together with minute flakes of mica (spotted schist, Knotenschiefer). A third and final stage is reached when, by the increase of the mica and quartz-grains, the rock passes into mica-schist—a light or bluish-gray rock, with wonderfully contorted foliation, which is developed close to the granite, there being

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[21] De la Beche, "Report on Geology of Devon and Cornwall," Mem. Geol. Survey, 1839, p. 268. See also Forbes, Trans. Geol. Soc. Cornwall, ii. p. 260, and Boase, op. cit. iv. 1832, p. 166. The microscopic structure of the unaltered slates of Cornwall has been described by Allport, Q. J. Geol. Soc. xxxii. 1876, p. 407, and that of the greenstones by J. A. Phillips, op. cit. xxxiv. 1878. Some interesting observations on the metamorphism of Cornish and other slates are given by Sorby in his Address to the Geological Society, op. cit. xxxvi. 1880, p. 81 *et seq.*

always a sharp line of demarcation between the mica-schist and the granite.[22]

In the same region the granite boss of Shap has produced some interesting changes on the andesitic and rhyolitic lavas and tuffs associated with the Lower Silurian strata. These changes have been studied by Messrs. Harker and Marr, who describe the gradual alteration of the andesites by the development of brown mica, hornblende, sphene, and other minerals. The amygdaloidal cavities had been filled with secondary products, and the rocks had thus been considerably weathered before the intrusion of the granite, for the materials filling the vesicles partake in the general metamorphism. By the gradual increase of the brown mica and the production of a marked laminated structure indicated by the parallel disposition of the mica-flakes, these lavas and tuffs assume the aspect of true crystalline schists.[23]

Further north, in the southwestern counties of Scotland, several large masses of fine-grained granite rise through the Lower Silurian graywacke and shale, which, around the granite for a variable distance of a few hundred yards to nearly two miles, have undergone great alteration (see Fig. 282). These strata are ranged in steep anticlinal and synclinal folds which run across the south of Scotland in a general northeast and southwest direction. It is observable that this normal strike continues, with little modification, up to the granite, which thus has replaced an equivalent area of sedimentary rock (see p. 947). The coarser arenaceous beds, as they approach the granite, are changed into quartz-rock, the thin siliceous shales into Lydian-stone, the black anthracitic graptolite-shales into a compact mass charged with pyrites, and breaking into large rough blocks. Strata wherein felspar-grains abound have been altered to a greater distance than the more siliceous beds, and show a gradation through spotted schists, with an increasing development of mica and foliation, until along the edge of the granite they become true mica-schist and even a fine kind of gneiss.[24] The pebbly conglomerates which form a marked horizon among the unaltered rocks, are traceable in the

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[22] J. C. Ward, Q. Journ. Geol. Soc. xxxii. 1876, p. 1. Compare the development of andalusite in regional metamorphism, p. 1040, note.

[23] Harker and Marr, Q. J. Geol. Soc. xlvii. 1891, p. 266.

[24] J. Horne, Mem. Geol. Surv. Scotland, Explanation of Sheet 9, p. 22. Brit. Assoc. 1892, p. 712. The microscopic structure of the altered rocks in this district has been studied by Prof. Bonney and Mr. Allport, Proc. Roy. Soc. xlvi. 1889, and Miss M. J. Gardiner, Q. J. Geol. Soc. xlvi. 1890, p. 569.

metamorphosed areole as rocks which, at first sight, might be taken for some kind of porphyritic gneiss. Their quartz-pebbles have assumed a resinous aspect, and are enveloped in a crystalline micaceous paste. The metamorphism of the Highlands is referred to on p. 1036 and in Book VI. Part I. § ii.

A classical region for the study of contact-metamorphism is in the Harz, where, round the granite masses of the Brocken and Ramberg, the Devonian and older Palæozoic rocks are altered into various flinty slates and schists which form a ring round the eruptive rock. Dikes and other masses of a crystalline diabase have likewise been erupted through the graywackes and shales, which, in contact and for a varying distance beyond, have been converted into hard siliceous bands (hornstone) and into various finely foliated masses (fleckschiefer, bandschiefer, contactschiefer, the spilosite and desmosite of Zincken). The limestones have their carbon-dioxide replaced by silica in a broad zone of lime-silicate along the contact.[25] The black compact limestone of Haserode becomes a white saccharoid marble, charged with silicates (rhombic dodecahedrons of garnet, etc.) and with its carbonaceous matter segregated into abundant veins. A limestone band containing ironstone presents, in the Spitzenberg between Altenau and Harzburg, a garnetiferous magnetite containing well-preserved crinoid stems.[26]

Round the syenite of Meissen, in Saxony, the diabases when they come within the areole of contact-metamorphism pass into actinolite-schists and anthophyllite-schists.[27]

The French Pyrenees present instructive examples of the effect of the protrusion of granite and other eruptive rocks upon Cambrian and later formations. Fuchs has traced the metamorphism of clay-slate through spotted schists (frucht-, chiastolite-, and andalusite-schists) into mica-schist and gneiss.[28] More recently the region has

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[25] Zincken, Karsten und v. Dechen, Archiv, v. p. 345; xix. p. 583. Fuchs, N. Jahrb. 1862, pp. 769, 929. K. A. Lossen, Z. Deutsch. Geol. Ges. xix. p. 509 (on the Taunus); xxi. p. 291; xxiv. p. 701. Kayser, op. cit. xxii. p. 103. The memoirs of Lossen form some of the most important contributions to our knowledge of the phenomena of metamorphism.

[26] K. A. Lossen, Z. Deutsch. Geol. Ges. xxix. 1877, p. 206. Erläuter. Geol. Special-Kart. Preuss. Blatt, Harzgerode, 1882.

[27] K. Dalmar, Blatt 64 (Tanneberg), Erläuter. Special-Kart. Sachsen, 1889; A. Sauer, op. cit. Blatt 48 (Meissen).

[28] N. Jahrb. 1870, p. 742; see also Zirkel, Zeitsch. Deutsch. Geol. Ges. xix. 1867, p. 175.

been studied in great detail by Barrois, who distinguishes three successive zones in the metamorphic areola surrounding the granite. On the outside lies the zone of "goffered schists," in which a puckered structure has been developed without any new mineral combination of the elements of the rock. Next come the chiastolite-schists, with crystals of chiastolite, tourmaline, etc., which become more and more micaceous toward the interior, till they pass into the third and innermost zone, that of the leptinolites, which are highly micaceous schists with small crystals of chiastolite, and sometimes with tourmaline, rutile and triclinic felspar. Barrois also shows that round the masses of kersantite a ring of chloritic mica-schist has been developed, followed outside by one of spotted schists.[29]

Some important observations have been made by Barrois at Guémémé, in the maritime department of Morbihan, where Lower Silurian strata have been invaded by granite. Of special interest are the effects produced upon the sandstones (grès à scolithes), which are converted into micaceous quartzites. These altered rocks, traced further inward, are further distinguished by the development in them of sillimanite, sometimes in sufficient abundance to impart a foliated, undulated, gneissoid structure. At the contact with the eruptive rock, this quartzite shows recrystallized quartz, black mica, sillimanite, cordierite, and a good many crystals of orthoclase and plagioclase, besides white mica. The conglomerates show their matrix altered into a mass composed of rounded or angular grains of quartz united by abundant white sericitic mica, and containing some crystals of zircon, large plates of muscovite, and yellow granules of limonite.[30]

Another admirable locality for the study of contact-metamorphism is the eastern Vosges. Rosenbusch, in describing the phenomena there, has shown that the unaltered clay-slates are gray, brown, violet, or black, thinly fissile, here and there curved, crumpled, and crowded with kernels and strings of quartz.[31] Traced toward the granite of Barr Andlau, they present an increasingly pronounced metamorphism.

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[29] "Recherches sur les Terrans anciens des Asturies et de la Galice," quarto, Lille, 1882.

[30] Ann. Soc. Geol. Nord, xi. 1884, p. 103. Compare also the early observation of Puillon-Boblaye regarding trilobites and orthids in chiastolite slates, Comptes Rend. vi. 1836, p. 168, confirmed by the Comte de Limur, Bull. Soc. Geol. France (3), xiii. 1885, p. 55.

[31] N. Jahrb. 1875, p. 849. "Die Steigerschiefer und ihre Contact-Zone," Strassburg, 1877. Unger, N. Jahrb. 1876, p. 785.

First they assume a spotted appearance, owing to the development of small dark points and knots, which increase in size and number toward the granite, while the ground-mass remains unaltered (knotenschiefer, fruchtschiefer). The ground-mass of the slate then becomes lighter in color, harder, and more crystalline in appearance, while flakes of mica and quartz-grains make their appearance. The knots, now broken up, rather increase than diminish in size; the hardness of the rock rapidly increases, and the fissile structure becomes unrecognizable on a fresh fracture, though observable on a weathered surface. Still nearer the granite, the knot-like concretions disappear from the rock, which then has become an entirely crystalline mass, in which, with the lens, small flakes of mica and grains of quartz can be seen, and which under the microscope appears as a thoroughly crystalline aggregate of andalusite, quartz, and mica. The proportions of the ingredients vary, but the andalusite and quartz usually greatly preponderate (andalusite-schist). Chemical analysis shows that the unaltered clay-slate and the crystalline andalusite-schist next the granite consist essentially of similar chemical materials, and that "probably the metamorphism has not taken place by the addition or subtraction of matter, but by another and still unknown process of molecular transposition."[32] In some cases, boric acid has been supplied to the schists at the contact.[33] Still more striking, perhaps, is the condition of the rocks at Rothau; they have become hornblendic, and their included corals have been replaced, without being distorted, by crystals of hornblende, garnet, and axinite.[34]

In the Christiania district of southern Norway, singularly clear illustrations of the metamorphism of sedimentary rocks round eruptive granite have long been known. Kjerulf has shown that each lithological zone of the Silurian formations, as it approaches the granite of that district, assumes its own distinctive kind of metamorphism. The limestones become marble, with crystals of tremolite and idocrase. The calcareous and marly shales are changed into hard, almost jaspery, shales or slates; the cement-stone nodules in the shales appear as masses of garnet; the sandy strata become hard siliceous schists (hälleflinta, jasper, hornstone) or quartzite; the non-calcareous black clay-slates are

[32] Unger, op. cit. p. 806.
[33] Rosenbusch, "Die Steigerschiefer," etc., p. 257.
[34] Ann. des Mines, 5me ser. xii. p. 318.

converted into chiastolite-schists, or graphitic schists, but often show to the eye only trifling alteration. Other shaly beds have assumed a fine glimmering appearance; and, in the calcareous sandstone, biotite has been developed. In spite of the metamorphism, however, neither fossils nor stratification have been quite obliterated from the altered rocks. From all the stratigraphical zones fossils have been found in the altered belt, so that the true position of the metamorphosed rocks admits of no doubt.[35] Prof. W. C. Brögger has subjected the rocks of the zones of contact-metamorphism round Christiania to a searching microscopic examination, and has published a highly important and interesting memoir on the subject. He describes the unaltered and altered conditions of the more conspicuous stratigraphical bands, and thus provides new material for the investigation of contact-metamorphism. Especially interesting are his descriptions of the distinctive metamorphism of each band, the remarkably variable amount of alteration even in the same band, the persistence of recognizable graptolites even in rocks that have become essentially crystalline, the transformation of limestone into marble, of which a fourth or fifth part is composed of garnet, partly in large rhombic dodecahedrons, and partly as a mold inclosing *Orthis calligramma.*[36]

One further European example may be cited from the observations of F. E. Müller, who has described round the granite of the Hennberg near Lehesten in the Frankenwald the occurrence of knotted schists, chiastolite-schists, knotted mica-schists, and andalusitic mica-rocks.[37]

The same phenomena have been observed in many other parts of the world. One example from America may suffice to show how precisely the facts collected in the Old World are repeated in the New. An elaborate examination was made of the contact-metamorphism of the granite of Albany, New Hampshire, by the late Mr. G. W. Hawes.[38] His analyses indicate a systematic and progressive series of changes in the schists as they approach the granite. The rocks are dehydrated, boric and silicic acids have been added to them, and there appears to have been also an infusion of alkali directly on the contact. He regarded the schists as

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[35] "Geologie Norwegens," 1880, p. 75. For the literature of the Norwegian locality see E. Reyer, Jahrb. Geol. Reichsanst. xxx. 1880, p. 26.

[36] "Die Silurischen Etagen 2 und 3 im Kristiania Gebiet," Kristiania, 1882.

[37] Neues Jahrb. 1882 (2), p. 205.

[38] Amer. Journ. Sci. xxi. 1881, p. 21.

having been impregnated by very hot vapors and solutions emanating from the granite.

Alteration of the Intrusive Rock.—Reference has been made above (p. 948) to the possible alteration of composition in an eruptive mass by fusing into itself some portion of the rocks through which it is intruded, and also to the remarkable change superinduced upon intrusive sills of diabase by contact with carbonaceous strata. Dr. Stecher, to whom I sent a carefully collected series of specimens illustrative of the intrusive sheets of the basin of the Firth of Forth and their contact phenomena, has investigated this question and obtained some interesting results. He shows that along the edges of contact with the sandstones or shales these diabases present a great abundance of well-defined crystals of olivine, that as the rock is examined progressively further from the contact these crystals become more or less corroded, while in the centre of the sheet they so entirely disappear that the rock appears as a diabase without olivine. He finds that the interior parts of the mass are more acid than the exterior parts, and he attributes this difference to the incorporation of silica from rocks (sandstones, etc.) broken through by the diabase. The outer olivine-bearing selvage he regards as representing the original composition of the rock at the time of its extrusion, and he thinks that the assimilation of acid material by the central still fluid and slowly cooling portion led to the corrosion and re-solution of the olivine which at the time of extrusion, as proved by the marginal selvage, was already perfectly crystallized out. In some of the rocks he found a surplus of silica which had crystallized as quartz. Recognizing that the first portion to take definite crystalline form would be more basic than the still liquid

portions, he yet concludes that this will not account for the observed facts, which in his opinion point to an actual addition of silica.[39] It is very desirable that similar careful chemical and microscopic investigation should be undertaken with a special view to the determination of the difference in chemical constitution between the peripheral and central portions of intrusive masses, and to ascertain whether any such difference can be traced to the influence of the rocks through which these masses have been erupted.

Summary of Facts.—The foregoing examples of the alteration superinduced upon stratified rocks in proximity to granite or other eruptive masses might be largely increased; but they may suffice to establish the following deductions in regard to contact-metamorphism.

1. Groups of ordinary sedimentary strata, likewise eruptive rocks associated with them, where they have been pierced by granite or other plutonic rock, have undergone an internal change, whereby their usual lithological characters have been partially or wholly obliterated. This alteration, however, is not always observable at the contact of intrusive masses, and we do not yet know the precise conditions that have determined its development.

2. The distance to which the change extends varies within wide limits, being in some cases scarcely traceable for more than a few feet, in others continuing for two miles or more. The subterranean surface of the plutonic rock, however, being unknown, may frequently lie nearer the surface of the ground than might be supposed. Detached minor areas of metamorphism may thus be connected with

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[39] Stecher, "Contact-Erscheinungen an Schottischen Diabasen," Tschermak's Mittheil. ix. 1887, pp. 145–205.

eruptive bosses which have not yet been laid bare by denudation.

3. As the alteration increases in intensity with greater proximity to the plutonic rock, it must be regarded as a result of the protrusion of that rock. But there occur exceptional areas or bands which have undergone a minor degree of change even in the midst of highly altered portions.

4. The character of the metamorphism depends fundamentally upon the nature and mass of the invading rock and on the composition and texture of the materials which have been affected. Sandstones have been changed into quartzite; siliceous schists into hornstone, Lydian-stone, etc.; clay-slates into spotted schists, chiastolite-schists, mica-schists, etc.; argillaceous graywacke and graywacke-slate into "knotenschiefer," mica-slate, and gneiss; limestone into garnet, hornblende, and other minerals. Alternations of distinct kinds of sedimentary strata, such as slate and sandstone, are represented by distinct alternating metamorphic bands, such as quartzite and mica-schist.

5. In some cases, the transformation of a thoroughly clastic rock (clay-slate, graywacke, graywacke-slate, or flagstone) into a completely crystalline one (andalusite-schist, mica-schist, gneiss) has been effected with little or no alteration of the ultimate chemical composition of the mass. In other cases a perceptible alteration in the proportions of the chemical ingredients is traceable.[40] The

[40] This is specially noticeable in the proportion of silica, which is sometimes found to be largely increased in the altered zone, either by an absolute addition of this acid, or by solution and removal of some of the bases. See Kayser, Z. Deutsch. Geol. Ges. xxii. p. 153. The development also of such minerals as tourmaline suggests that boric and other acids have been introduced into the rocks.

development of a crystalline structure can be followed through intermediate stages from ordinary sedimentary rock to thoroughly crystalline schist, remains of fossils being still observable after considerable progress has been made toward the completion of a crystalline rearrangement.

6. Not only does the crystalline character increase toward the limit of contact with the eruptive rock, but it is not infrequently accompanied with a progressive development of foliation, the minerals, more especially the mica, crystallizing in folia parallel either with the original stratification of the clastic mass or with cleavage surfaces, should these be its dominant divisional planes.[41] Along the line of contact with granite, the foliation is sometimes excessively crumpled or puckered.

7. The phenomena of alteration observed round intrusive masses of such rocks as diabase and basalt undoubtedly point to the heat of the eruptive rock as their prime cause. Those that occur round the deeper-seated bosses of granitic rocks have probably involved other influences than mere heat; they so closely resemble those of regional metamorphism as to suggest modifications of one common cause for them both. In any case, mere dry heat would probably have been ineffective for the production of the more marked phases of the contact-metamorphism round granite. It was accompanied by the co-operation of water, either already present interstitially in the sedimentary rocks, or supplied to them from the eruptive mass, possibly combined with various mineralizing agents and acting under considerable pressure. Moreover, the intrusion of large bosses of eruptive rock not improbably gave rise to mechanical move-

[41] In the south of Scotland the foliation round the granite bosses is coincident with stratification; round Skiddaw, with cleavage.

ments in the surrounding parts of the crust, and thereby stimulated crystalline rearrangements, such as have undoubtedly been generated by crushing, plication, and other movements in areas of regional metamorphism.

§ ii. Regional (Normal) Metamorphism—the Crystalline Schists

From the phenomena of metamorphism round a central boss of eruptive rock, we now pass to the consideration of cases where the metamorphism has affected wide areas without visible relation to eruptive matter. It is clear that only those examples are here admissible in evidence where there is distinct proof that what are called metamorphic rocks either pass into masses which have not been metamorphosed, or present characters which are elsewhere proved to have been produced by the alteration either of stratified or of massive rocks.

In the study of this difficult but profoundly interesting geological problem, it is desirable to begin with the examination of rocks in which only the slightest traces of alteration are discernible, and to follow the gradually increasing metamorphism, until we arrive at the most perfectly developed crystalline schists. It is the earliest stages which are of most importance, for it is there that the nature and proofs of the changes can best be established. As already remarked (p. 990), the igneous rocks, from the definiteness of their original structure and composition, offer special facilities for following the nature and extent of the changes involved in the metamorphism of a region or a large series of rocks.

The extent and character of the metamorphism depend in the first place upon the original constitution of the rock,

and in the second place upon the energy of the metamorphic agents. Certain rocks resist alteration. Pure siliceous sandstones, for example, become quartzites, but advance no further, though occasionally, under intense strain, their particles are drawn out into a somewhat schistose arrangement. But where felspathic elements are present, particularly where they are the chief constituents, some form of mica almost invariably appears, while new minerals and structures may be developed in progressively increasing abundance, till the rock assumes the character of a true crystalline schist.

Possessing characters which link them, on the one hand, with stratified, on the other, with eruptive rocks, the Crystalline Schists present a peculiar type of structure with which are connected some of the most perplexing problems of geology. These rocks cover extensive areas of the surface of the continents, occurring usually wherever the oldest formations have been brought to light. But they everywhere pass under younger formations, so that their visible superficies is probably but a very small part of their total extent. In the northern regions of Europe and of North America, they spread over thousands of square miles, forming the table-land of Scandinavia, the Highlands of Scotland, and a great part of Eastern Canada and Labrador. They likewise commonly rise to the surface along the axes of great mountain-chains in all quarters of the globe. So persistent are they, that the belief has arisen that they everywhere underlie the stratified formations as a general foundation or platform. Some details of their structure will be given in the description of Pre-Cambrian Rocks in Book VI.

The most distinctive character of the schists is undoubt-

edly their foliation (pp. 183, 304). They have usually a more or less conspicuous crystalline structure, though occasionally this is associated with traces, and even very prominent manifestations, of clastic ingredients (pp. 312, 1040). Their foliated or schistose structure varies from the massive type of the coarsest gneiss down to the extremely delicate arrangement of the finest talcose or micaceous schist. They occur sometimes in monotonous uniformity: one rock, such as gneiss or mica-schist, covering vast areas. In other places, they consist of rapid alternations of various foliated masses—gneiss, mica-schist, clay-slate, actinolite-schist, and many other species and varieties. Lenticular seams of crystalline limestone or marble and dolomite, usually with some of the minerals mentioned on p. 264, sometimes strongly graphitic, not infrequently occur among them, especially where they contain bands of serpentine or other magnesian silicates. Thick irregular zones of magnetite, hæmatite, and aggregates of hornblendic, pyroxenic, or chrysolitic minerals likewise make their appearance.

Another characteristic of the schists is their usual intense crumpling and plication. The thin folia of their different component minerals are intricately and minutely puckered (Figs. 36, 37). Thicker bands may be traced in violent plication along the face of exposed crags. So intense indeed have been the internal movements of these masses, that the geologist experiences great and often insurmountable difficulties in trying to make out their order of succession and their thickness, more especially as he cannot rely on the banding of the rocks as always or even generally an indication of consecutive deposition. Such evidence of disturbance, though usually strongly marked, is not everywhere equally so. Some areas have

been more intensely crumpled and plicated, and where this is the case the rocks usually present their most conspicuously crystalline structure.

A further eminently characteristic feature of the schists is their common association with bosses and veins or bed-like sheets of granite, syenite, quartz-porphyry, diorite, gabbro, or other massive rocks. In some regions, indeed, so abundant are the granitic masses and so coarsely crystalline or granitoid are the schists, that it becomes impossible to draw satisfactory boundary-lines between the two kinds of rock, and the conviction arises that in some cases they represent different conditions of the same original material, while in others the result is due to granitization (p. 1002).

The question of the formation and geological age of the crystalline schists has given rise to much controversy. Some geologists have maintained that these rocks are to be regarded as portions of the early crust of the globe which consolidated from a molten condition. Others have regarded them as original chemical deposits on the floor of a primeval ocean. These writers, justly repudiating the exaggerated views of those who have sought by metamorphic (metasomatic) processes to derive the most utterly different rocks from each other (for example, limestone from gneiss and granite, granite and gneiss from limestone, talc from granite, etc), have insisted that the crystalline schists, in common with many pyroxenic and hornblendic rocks (diabases, gabbros, diorites, etc.), as well as masses in which serpentine, talc, chlorite, and epidote are prevailing minerals, have been deposited "for the most part as chemically-formed sediments or precipitates, and that the subsequent changes have been simply molecular, or at most confined in certain cases to reactions between the mingled elements

of the sediments, with the elimination of water and carbonic acid." To support this view, it is necessary to suppose that the rocks in question were formed during a period of the earth's history when the ocean had a considerably different relative proportion of mineral substances dissolved in its (then probably much warmer) waters; they are consequently assigned to a very early geological period, anterior indeed to what are usually termed the Palæozoic ages. It becomes further needful to discredit the belief that any gneiss or schist can belong to one of the later stages of the geological record, except doubtfully and merely locally. The more thoroughgoing advocates of the pristine, "azoic," or "eozoic," date, of the so-called "Metamorphic" or crystalline schists, do not hesitate to take this step, and endeavor, by ingenious explanations, to show that the majority of geologists (as in the case of the Alps, afterward referred to) have mistaken the geological structure of the districts where these rocks have been supposed to be metamorphosed equivalents of what elsewhere are Palæozoic, Secondary, or Tertiary strata.[43] Some of them even go so far as to assert that, by mere mineral characters, the crystalline rocks of contemporaneous periods can be identified all over the world. They assume that in the supposed chemical precipitation, the same general order has been followed everywhere over the floor of the ocean. Consequently a few hand-specimens of the crystalline rocks of a country are enough in their eyes to determine the geological position of these formations. Other geologists, recognizing that the more crystalline members of the series of schists graduate into rocks that are much less crystalline, and even into

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[43] See Sterry Hunt's "Chemical Essays," p. 382 *et seq.*

what are recognizably of sedimentary origin, likewise that they include and pass into masses that were certainly eruptive, have come to regard the schists as a metamorphic series of sedimentary and igneous rocks owing their characteristic foliated structure to some subsequent action upon them.

One of the chief causes of difficulty in discussing the history of these rocks has lain in the fact that the crystalline schists are, in the majority of cases, separated from all other geological formations by an abrupt hiatus.[43] Instead of passing into these formations, they are commonly covered unconformably by them, and have usually been enormously denuded before the deposition of the oldest overlying rocks. Hence, not only is there generally a want of continuity between the schists and younger formations, but the contrast between them, in regard to lithological characters and geotectonic structure, is often so exceedingly striking as naturally to suggest the idea that the schists must belong to a far earlier period than that of the oldest sedimentary formations of the ordinary type, and to a totally different order of physical conditions. Natural, however, as this conclusion may be, those who adopt it probably seldom realize to what an extent it rests upon mere assumption. Starting with the supposition that the crystalline schists are the result of geological operations that preceded the times when ordinary sedimentation began, it assumes that they belong to one great early geological period. Yet all that can logically be asserted as to the age of these rocks is that they must

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[43] Many Continental geologists, however, believe that the foliation of the schists is usually parallel to the stratification of the immediately overlying sedimentary formations. See, for instance, the summary given by M. Michel-Lévy, Bull. Soc. Geol. France, xvi. 1888, p. 102.

be older than the oldest formations which overlie them. If in one region of the globe they appear from under Cretaceous, in another below Carboniferous, in a third below Silurian strata, their chronology is not more accurately definable from this relation than by saying they are respectively pre-Cretaceous, pre-Carboniferous, and pre-Silurian. They may all of course belong to the same period; but where they occur in detached and distant areas, there is as yet no method whereby their synchronism can be proved. To assert it is an assumption which, though in many cases irresistible, ought not to be received with the confidence of an established truth in geology.

In the investigation of the problem of the crystalline schists, much assistance may be derived from a study of the localities where a crystalline and foliated structure has been superinduced upon ordinary sedimentary and eruptive rocks —where, in fact, these rocks have actually been changed into schists, and where the gradation between their unaltered and their altered condition can be clearly traced. In recent years so much attention has been given to these transformations that our knowledge of metamorphic processes has been greatly extended, and the problem of regional metamorphism, though by no means entirely solved, is at least much more clearly understood than it has ever been before.

There is now a general agreement among geologists that a fundamental condition for the production of extensive mineralogical alteration of rocks has been disturbance of the terrestrial crust, involving the intense compression, crushing, fracturing, and stretching of masses of rock. Compression, as we have seen, may give rise to slaty cleavage (p. 532). But the same kind of force has re-

sulted in a further change, wherein chemical reactions have been set up and new minerals have been formed. The effects of pressure and of movement under great strain in quickening chemical activity are now clearly recognized. Not only have the original minerals been driven to rearrange themselves with their long axes perpendicular to the direction of the pressure, but secondary minerals with well-marked cleavage have been developed along the same lines and thus a distinct foliated structure has been induced in what were originally amorphous rocks.

Still more marked are the transformations where the rocks have not merely been compressed, but where they have been crushed, fractured, or stretched. The extraordinary manner in which the crust of the earth has been fractured in some areas of regional metamorphism has been worked out in great detail by the Geological Survey in the northwest of Scotland.[44] We there perceive how slice after slice of solid rock has been pushed forward one over the other, how those accumulated slices have been driven over others of similar kind, how this structure has been repeated again and again, not only on a great scale involving mountain-masses in the movement, but even on so minute a scale that the ruptures and puckerings cannot be seen without a microscope (p. 1033).

Such dynamical movements could not but be accompanied with widespread and very marked chemical change. Along the margins of faults or planes of shearing, where the rocks have been ground against each other, there is a selvage of foliated material which with its new mineral combinations gradually passes into the amorphous rock on either

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[44] Quart. Journ. Geol. Soc. xliv. 1888, p. 378.

side. In such places sericite, biotite, chlorite, or some other secondary product with its cleavage planes ranged in one common direction, shows the line of movement and the reality of the chemical recombinations. In the body of a mass of rock, also, subject to great strain, relief has been obtained by crushing along certain planes, with a consequent greater development of the secondary minerals along these planes, and the production of a banded or schistose structure in a rock that may have been originally quite homogeneous.[45]

The recognition of the powerful part taken by mechanical deformation in producing the characteristic structures of many schistose rocks has not unnaturally led to some exaggeration on the part of geologists, who were thus provided with what appeared to be a solution of difficulties which at one time seemed insuperable. There can hardly be any doubt that the theory of mechanical deformation has been too freely used and has been applied to structures to which it cannot properly be assigned. Among the coarser gneisses, for example, the segregation of the component minerals in more or less parallel lenticular bands is a structure that seems to find its nearest analogy rather among the segregation-veins of eruptive bosses and sheets than among sheared, cleaved, and foliated rocks, such as undoubtedly have been the originals of many schists. There is nothing to show that this parallel banding is not an arrangement of the materials of an igneous magma before final consolidation.

But while this tendency to a too liberal use of dynamical causes in explication of all the structures of the crystalline schists must be admitted, we are now furnished with ample evidence of the efficacy of mechanical movements in the

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[45] G. H. Williams, Bull. U. S. Geol. Surv. No. 62, 1890, pp. 202–207.

production of regional metamorphism. It is frequently possible to detect portions of the original structures, to show that they belonged to certain familiar and definite types of sedimentary or eruptive rocks, and to trace every stage of transition from them into the most perfectly developed crystalline schist. In the crushing down of large masses of rock during powerful terrestrial movements, lenticular cores of the rocks have frequently escaped entire destruction. Round these cores the pulverized material of the rest of the rock has been made to flow, somewhat like the flow-structure round the porphyritic crystals of a cooling lava. And successive gradations may be followed until the cores, becoming smaller by degrees, pass finally into the general reconstructed material. That this structure is not original, but has been superinduced upon the rocks after their solidification can be abundantly demonstrated. Among the sedimentary formations the elongation and flattening of the pebbles in conglomerates, and the transition from grits or graywackes into foliated masses, prove the structure to have been superinduced. Among eruptive rocks the crushing down of the original minerals, and their transformation into others characteristic of foliated rocks, afford the same kind of proof.[46]

[46] On the mechanical deformation and dynamical metamorphism of rocks see A. Heim, "Untersuchungen über den Mechanismus der Gebirgsbildung," 1878; A. Rothpletz, Zeitsch. Deutsch. Geol. Gesell. xxxi. 1879, p. 374; H. Reusch, "Die fossilien-führenden Krystallinischen Schiefer von Bergen," German translation by Baldauf, 1883. Neues Jahrb. (Beilageband), 1887, p. 56; "Bömmelöen og Karmöen," 1888; Rep. Geol. Congress, London, 1891, p. 192; Lehmann, "Untersuchungen über die Entstehung der altkrystallinischen Schiefer," 1884; J. J. H. Teall, Geol. Mag. 1886, p. 481; G. H. Williams, Bull. U. S. Geol. Survey, No. 62, 1890. For an instance of the metamorphism of a conglomerate into albite schist see J. E. Wolff, Bull. Mus. Comp. Zool. Harvard, xvi. No. 10, p. 174, 1891. The Papers on the Crystalline Schists by Heim, Lory, Lehmann, Michel-Lévy, Lawson, and the U. S. Geol. Survey in the report of the London Session of the International Geological Congress (published in 1891) should also be consulted.

So great has been the pressure exerted by gigantic earth-movements upon the rocks of the crust that even the most solid and massive materials have been sheared, and their component minerals have been made to move upon each other, giving a flow-structure like that artificially produced in metals and other solid bodies (ante, p. 538). But it may be doubted whether this motion is ever strictly molecular without rupture of the constituent minerals. Microscopic examination shows that, at least as a general rule, the minerals in the most thoroughly bent and crushed rocks have been broken down. It is observable that under the effects of mechanical strain the minerals first undergo lamellation, twinning being developed along certain planes. This structure increases in distinctness with the intensity of the strain so long as the mineral (such as felspar) retains its cohesion, but the limit of endurance is soon reached, beyond which it will crack and separate into fragments, which, if the movement is arrested at this stage, may be cemented together by some secondary mineral filling up the interspaces. But should the pressure increase, the mineral may be so wholly pulverized as to assume a finely granular structure or mosaic of interlocking grains, which under the influence of continual shearing may develop a streaky arrangement, as in flow-structure and foliation.[47]

One of the most important effects of this mechanical deformation and trituration under gigantic pressures has been the great stimulus thereby given to chemical reactions. So constant and so great have these reactions been, and so completely in many cases have the ingredients of the rocks been recrystallized in fresh combinations, that the new structures

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[47] Lehmann, op. cit. pp. 245, 249; G. H. Williams, Bull. U. S. Geol. Survey. No 62, p. 47.

thus produced have masked the proof of the mechanical deformations that preceded or accompanied them. It is in the main to the light thrown on the subject by the microscopical investigation of the minute structures of the metamorphosed masses that we are indebted for the recognition of the important part played by pressure and stretching in the production of the more essential and characteristic features of metamorphic rocks. Many chemical rearrangements may undoubtedly take place apart from any such dynamical stresses, but none of these stresses appears to have affected the metamorphic rocks without being accompanied by chemical and mineralogical readjustments.

The mineral transformations observable in regional metamorphism "may consist (1) in the breaking up of one molecule into two or more with but little replacement of substance, as in the formation of saussurite from labradorite; (2) in a reaction between two contiguous minerals, each supplying a part of the substance necessary to form a new compound of intermediate composition, more stable for the then existing conditions than either, as in the formation of a hornblende zone between crystals of olivine or hypersthene and plagioclase; or (3) in more complicated and less easily understood chemical reactions, like the formation of garnet or mica from materials which have been brought together from a distance, and under circumstances of which it is at present impossible to state anything with certainty." [48] The following transformations especially deserve attention.

Micasization—the production of mica as a secondary mineral from felspars or other original constituents. One of the

[48] G. H. Williams, Bull. U. S. Geol. Survey, No. 62, p. 50. This admirable essay, with its copious bibliography, will well repay the careful perusal of the student. I am indebted to it for the abstract of metamorphic processes above given.

most common forms of this change is where the silky unctuous *sericite* has been developed from orthoclase (sericitization). The formation of mica is one of the most common results of the mechanical deformation of rocks, and is most conspicuous where the pressure or stretching has been most intense. Massive orthoclase rocks, such as granite, quartz-porphyry or felsite, when most severely crushed, pass into sericite schist; felspathic grits and slates may be similarly changed.[49]

Uralitization—the conversion of pyroxene into compact or fibrous hornblende. This change may not be a mere case of paramorphism or molecular rearrangement, but seems generally to involve a certain amount of chemical rearrangement, such as the surrender of part of the lime of the pyroxene toward the formation of such combinations as epidote,[50] and the higher oxidation of the iron.[51] It has taken place on the most extensive scale among the crystalline schists. Rocks which can be shown to have been originally eruptive, such as diabases, have been converted into epidiorite, and where the deformation has advanced further, into hornblende-schist or actinolite-schist.

Epidotization—the production of epidote in a rock from reactions between two or more minerals, especially between pyroxene or hornblende and plagioclase. In some cases diabases have been converted into epidiorites or aggregates of epidote and quartz or calcite.[52]

Saussuritization—the alteration of plagioclase into an aggregate of needles, prisms, or grains (chiefly zoisite), imbedded in a glass-like matrix (albite), by an exchange of silica and alkali for lime, iron, and water. This change has largely affected the felspar of coarse gabbros or euphotides, especially in districts of regional metamorphism.[53]

Albitization—a process in which, while the lime of the plagioclase is removed or crystallizes as calcite, instead of forming a lime-silicate like epidote or zoisite, the rest of the original mineral recrystallizes as a finely granular aggregate or mosaic of clear grains of albite. Examples of this change

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49 See especially Lehmann's "Untersuchungen über die Entstehung der altkrystallinschen Schiefergesteine," where the development of sericite as a result of mechanical deformation is well enforced.

50 Rosenbusch, "Mikrosk. Phys." 2d edition, 1887, p. 185.

51 J. J. H. Teall, Quart. Journ. Geol. Soc. xli. 1885, p. 137.

52 A. Schenck, "Die Diabase der oberen Ruhrthals," 1884.

53 Hagge, "Mikroskopische Untersuchungen über Gabbro," etc. Kiel, 1871, p. 51.

may be found in association with the development of saussurite.[54]

Chloritization—an alteration in which the pyroxene (or hornblende) of the so-called "greenstones" has been changed into secondary substances (1) more or less fibrous in structure allied to serpentine, not pleochroic but showing a decided action on polarized light; or (2) scaly, pleochroic, polarizing so weakly as to appear isotropic, and more or less resembling chlorite. This alteration is rather the result of weathering than of metamorphism in the strict sense.[55] Where chloritization and epidotization have proceeded simultaneously in aluminous pyroxene or hornblende, the result is an aggregate of sharply defined pale yellow crystals of epidote in a green scaly mass of chlorite.[56]

Serpentinization—an alteration more especially noticeable among the more highly basic igneous rocks in which olivine has been a prominent constituent. The gradual conversion of olivine into serpentine has been already described (p. 138), and the occurrence of massive serpentine has been referred to (p. 301).

Alterations of Titanic Iron.—The ilmenite or titaniferous magnetite of diabases and other eruptive rocks undergoes alteration along its margins and cracks into a dull gray substance (leucoxene, p. 130), which is now known to be a form of titanite or sphene. The gray rim frequently passes into well-defined aggregates and crystals of sphene.[57]

Marmarosis, or the alteration of an ordinary dull limestone into a crystalline-granular marble (p. 998), may be again referred to here as one of the characteristic transformations in regional metamorphism.

Dolomitization. See p. 546.

Granitization. See p. 960.

Production of New Minerals.—In tracts of regional metamorphism a number of secondary minerals may be observed to have crystallized out, and to be characteristic of the schistose rocks. Among the most conspicuous of these are white and black mica, garnet, quartz, epidote. Garnet occurs abundantly as a constituent of mica-schist and gneiss, and has resulted from the alteration of both clastic and massive rocks (compare p. 999).

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54 Lossen, Jahrb. Preuss. Geol. Landesanst. 1883, p. 640; 1884, pp. 525–530.
55 Rosenbusch, "Mikroskopische Physiographie," pp. 180–184.
56 G. H. Williams, Bull. U. S. Geol. Surv. No. 62, p. 56.
57 A. Cathrein, Zeitsch. Kryst. und Mineral. vi. 1882, p. 244.

A few illustrative examples of regional metamorphism, culled from different quarters of the globe, and various geological formations, may here be given. The subject is further discussed in Book VI. Part I.

Early Stages of Metamorphism.—In 1871 Zirkel showed that some of the clay-slates of the disturbed Silurian and Devonian tracts of central Europe contain minute microscopic needle-shaped microlites. Considerable diversity of opinion has arisen as to the nature of these rudimentary crystallizations. They have been regarded as microlites of hornblende, rutile, epidote, etc. More recently they have been carefully isolated, extracted, and analyzed by E. Kalkowsky, who regards them as staurolite, constituting from two to five per cent of the rock.[58] The whet-slate of Belgium has been found by Renard to be characterized by the presence of abundant garnets. Microscopic tourmaline and rutile likewise occur among clay-slates. No one would class as metamorphic the rocks in which these microlites occur, and yet the presence in them of microscopic microlites and crystals shows that they have undergone some of the initiatory stages of metamorphism, by the development of new minerals. All that is known of the probable origin of these minerals, negatives the supposition that they could have been formed in the original sediment of the sea-bottom on which the organisms entombed in the deposits lived and died. For their production, a temperature and a chemical composition of the water would seem to have been required such as must have been inimical to the co-existence in the same water of such highly organized forms of life as brachiopods and trilobites.

One of the most marked of the early stages of regional metamorphism is characterized by the appearance of fine scales of some micaceous mineral (muscovite, biotite, etc.). As these micaceous constituents increase in number and size, they impart a silky lustrous aspect to the surfaces on which they lie parallel. In many cases, these surfaces are probably those of original deposit, but where rocks have

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[58] Neues Jahrb. 1879, p. 382. These bodies are to be distinguished from the minute crystals of such durable minerals as zircon, rutile, etc., so often recognizable as clastic grains in sediments, and which may often have played a part in the sedimentation of more than one geological period.

been cleaved or sheared, the mica ranges itself along the planes of cleavage or shearing. The Cambrian tuffs of South Wales, of which the bedding still remains quite distinct, present interesting examples of the development of a mica along the laminæ of deposit.[59] The Dingle beds of Cork and Kerry, on the other hand, have been subjected to cleavage, and the mica appears along the cleavage planes, which have a lustrous surface. The Torridonian and Cambrian sandstones, quartzites and shales of northwest Scotland show a development of mica along the surfaces of the shearing-planes.

Ardennes.—As far back as 1848, Dumont published a description of the Belgian Ardennes, in which he showed that a zone of his "terrains ardennais et rhénan," had undergone a remarkable metamorphism. Sandstones, in approaching this zone, were transformed, he said, into quartzites, and by degrees passed into rocks characterized by the presence of garnet, hornblende, and other minerals; the slates (phyllades) graduated into dark rocks, in which magnetite, titanite, and ottrelite had been developed. Yet the fossiliferous character of the strata thus metamorphosed had not been destroyed. In specimens showing a gradation from a grit to a compact garnetiferous and hornblendic quartzite, Prof. Sandberger, to whom they were submitted, recognized the presence of the two Devonian shells, *Spirifer macropterus* and *Chonetes sarcinulatus*. "The garnets and the fossils are associated in the same specimen," he wrote, adding, "who, after this, can hesitate to admit that the crystalline schists and quartzites of the Hundsrück and Taunus are likewise metamorphosed Taunusian rocks?"[60]

In 1882 M. Renard, fortified with the resources of modern petrography, renewed the examination of Dumont's metamorphic area of the Ardennes, and conclusively established the accuracy of all the main facts noticed by the earlier observer. Not only do the geological structure of this region, and the occurrence of recognizable fossils, show that the rocks, now transformed into more or less crystalline masses, were originally parts of the ordinary series of Devonian sandstones, graywackes and shales, but the microscope comes in to confirm this conclusion. The original clastic grains of quartz and the diffused carbonaceous material of the unaltered strata can still be recognized in their metamorphosed equivalents. But there have been devel-

[59] Q. J. Geol. Soc. xxxix. 1883, p. 310. [60] Neues Jahrb. 1861, p. 677.

oped in them abundant new minerals—garnet (1 to 2 mm.), hornblende, mica, titanite, apatite, bastonite, ottrelite.[61]

Dumont appears to have believed that the metamorphism which he had traced so well in the Ardennes was to be attributed to the influence of underlying masses of eruptive rocks, though he frankly admitted that the metamorphism is less marked where eruptive veins have made their appearance than where they have not.[62] M. Renard, however, points out that eruptive rocks are really absent, and that the association of minerals proves that the metamorphosed rocks could not have been softened by a high temperature, as supposed by Dumont, otherwise the simultaneous presence of graphite and silicates, with protoxide iron bases, such as mica, hornblende, etc., would certainly have given rise at least to a partial production of metallic iron. He connects the metamorphism with the mechanical movements which the rocks have undergone along the altered zone.[63] The metamorphism of this region has since been described by Prof. Gosselet, who also regards it as due to dynamical causes.[64]

Taunus.—A similar example of regional metamorphism extends into the tracts of the Taunus and Hundsrück. In 1867 K. A. Lossen published an elaborate memoir on the structure of the Taunus, which is now of classic interest in the history of opinion regarding metamorphism.[65] He showed that below the middle Devonian limestone, the usual lower Devonian slates, graywackes and quartzites rise to the surface, but that these, traced southward, pass gradually into various crystalline schists. Among these schists, he distinguished sericite-gneiss, mica-schist, phyllite, knotted schist,

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[61] Renard (Bull. Mus. Roy. Belgique, i. 1882, p. 14) estimates the components of one of these altered rocks to be—

Graphite	4·80
Apatite	1·51
Titanite	1·02
Garnet	4·14
Mica	20·85
Hornblende	37·62
Quartz	30·62
Water	1·32
	101·88

[62] Renard, op. cit. p. 34. [63] Op. cit. p. 37.

[64] See his great Monograph on the Ardennes, Mem. Carte Geol. France, 1888, chap. xxv.

[65] "'Geognostische Beschreibung der linksrheinischen Fortsetzung des Taunus,'' etc., Z. Deutsch. Geol. Ges. xix. 1867, p. 509, 1885, p. 29.

augite-schist, sericite-lime-phyllite, quartzite and kieselschiefer. As intermediate grades between these crystalline masses and the ordinary clastic strata, he observed quartz-conglomerates, with a crystalline schistose matrix, or with albite crystals, and quartzites with sericite or mica. He concluded that while these crystalline rocks present the most complete analogies with those of the Alps, Silesia, Brazil, etc., they are yet so intimately bound up alike petrographically and stratigraphically with strata containing Devonian fossils, and into which they pass by semi-crystalline varieties, that they must be considered as of Devonian age. Subsequently K. Koch proposed to regard the crystalline schists of the Taunus as Cambrian (Huronian),[66] and they have been indicated on the Geological Survey map as Cambrian or Silurian. But the fact that a conformable sequence can be traced from undoubted fossiliferous Devonian strata downward into these crystalline schists makes it immaterial what stratigraphical name may be applied to them. They are almost certainly Devonian, as Lossen described them, and, in any case, they are unquestionably the metamorphosed equivalents of what are elsewhere ordinary sedimentary strata.

Scandinavia is mainly composed of crystalline schists which have been assigned to the so-called Archæan system. That some portions of them cannot be of so ancient a date was shown some years ago by Törnebohm in the uplands of Sweden. More recently similar deductions have been drawn from a study of the development of the rocks in Norway. At the Hardanger Fjord the following order of succession was established in 1875 and 1877 by W. C. Brögger:[67]

Crystalline schists (diorite-schists, hornblende-schists, garnetiferous mica-schists, true gneisses, etc.), the whole series becoming more and more crystalline toward the higher beds.	
Greenish micaceous schists (phyllites). This and the overlying group must be several thousand feet thick.	
Impure white marble (probably orthoceratite limestone)	30 feet
Blue quartz-sandstone	100 "
Black, little altered alum-schist, with Dictyograptus band	150 "

This section confirmed the early conclusion of Naumann that the great series of crystalline schists of the Norwe-

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[66] See Lossen's reply, Z. Deutsch. Geol. Ges. xxix. 1877, p. 341. He argues convincingly against the supposition that these can be original chemical deposits of Cambrian age. (See also Renard, Bull. Mus. Roy. Belg. i. p. 31, note.)

[67] "Die Silurischen Etagen 2 und 3 im Kristiania Gebiet," p. 352. The Swedish work of Törnebohm is referred to in Book VI. Part I. note 47.

gian uplands overlies the Silurian stage 2 in the Christiania district. Subsequently H. H. Reusch obtained from the Bergen district clear proof of the Silurian age of certain crystalline rocks in that part of Norway.[68] He found among masses of mica-schist, hornblende-schist, gneiss, and other crystalline rocks, intercalated bands of conglomerate which, while obviously of clastic origin, have undergone enormous compression, the pebbles being squeezed flat and the paste having become more or less crystalline. The occurrence of such bands suggests a sedimentary origin for the whole series of deposits. But from several localities he obtained fossils which have been recognized as undoubtedly Upper Silurian. Some of the fossils occur in a crystalline limestone, which is intercalated in a dark lustrous phyllite. But they are found, as casts, most abundantly in a light-gray lustrous micaceous schist, which, under the microscope, is observed to be composed in large measure of quartz, not having a fragmental aspect, with mica, rutile, and tourmaline. The fossils recognized comprise *Phacops*, *Calymene*, several undeterminable gasteropods and brachiopods, *Cyathophyllum*, *Halysites catenularia*, *Favosites*, *Rastrites*, *Monograptus*, and some others.

According to Reusch the sequence of rocks is continuous, and their thickness must be at least 16,000 feet. If we suppose that the fossiliferous zones have been brought into an older series by plication of the crust, the fact remains that the rock in which most of the fossils occur is itself a micaceous schist, like those among which it is imbedded, and therefore a metamorphic rock. It is consequently proved that some at least of the metamorphic rocks of Norway are of Silurian age, and are associated with evidence of great mechanical movements in the crust of the earth.

The Alps.—In the geological structure of the central Alps, crystalline schists play an important part. Originally these rocks were regarded as one series, of much more ancient date than the ordinary sedimentary formations, and of very different origin. The discovery of Silurian, Devo-

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[68] "Silurfossiler og Pressede Konglomerater i Bergensskifrene," Christiania, 1882; or the same work translated into German by R. Baldauf, "Die fossilienführenden krystallinischen Schiefer von Bergen in Norwegen," Leipzig, 1883. In the year 1889 I had an opportunity of personally going over Dr. Reusch's Bergen region and of collecting fossils from the rocks in which he found them. There can be no doubt that he has demonstrated that the metamorphism of that district has been connected with powerful dynamical movements, the latest of which are of younger date than the Upper Silurian period.

nian, Carboniferous, and Jurassic fossils in various schists and altered limestones surrounding the central gneiss, led to the belief that these are metamorphosed sedimentary rocks of Palæozoic, Mesozoic, and even of older Tertiary date. This belief has subsequently been attacked by several able observers, who, starting with the assumption that the crystalline schists must be everywhere of great relative antiquity, have endeavored to show that the fossiliferous bands intercalated among them have been brought into this position by plication, and that there is no evidence that any part of the schists is even of Palæozoic age.[69] Now it must be admitted that in the sections, even as drawn by those who adopt this explanation, the obvious and natural interpretation is that which has been so generally adopted—that the fossiliferous beds are actually part of the crystalline series in which they are imbedded. If the apparent order is deceptive, this must be proved by those who maintain it. If, however, we turn to their writings we find a good deal of strong assertion, and various more or less ingenious attempts to construct sections in which the abnormal position of the fossiliferous beds is to be accounted for. It does not appear to be realized that on the supposition of the high antiquity and original discordant infraposition of the schists, the chances are small that, in any plication of the mountains, the unconformable fossiliferous strata would become conformably stratified with ancient schists even at one locality. But when we look at the published sections of the Alps, and find that the parallelism between the schists and the inclosed fossiliferous bands occurs again and again at widely separated localities, and that in fact this is their normal position, it becomes utterly incredible that the conformability can be the result of plication, except on the supposition that the foliation of the schists is not their original structure, but a new one superinduced upon them at the time of the plication and metamorphism of the fossiliferous strata.[70]

Let us, however, grant, for the sake of argument, that

[69] Consult Lory, "Description geologique du Dauphiné," 1860, part i. §§ 40–42; Compte rendu Congres Geologique International, Paris, 1881, pp. 39–43; Bull. Soc. Geol. France, 3e serie, ix. 1881, pp. 652–679; Favre, "Recherches geologiques dans les parties de la Savoie, etc., voisines du Mt. Blanc," 1867, chaps. xxi. xxiv. xxv.; A. Müller, Mem. Soc. d'Hist. Nat. Bâle, 1865–70. See also Sismonda, Real. Acad. Sci. Torin. (2) xxiv. 1866, p. 333; Sterry Hunt, "Chem. Essays," pp. 283, 328. Bonney, Address, Quart. Journ. Geol. Soc. xlii. 1886, p. 38; xlvi. 1890, p. 187; and other papers cited, postea, p. 1035.

[70] See this structure illustrated by that of northwest Scotland, postea, p. 1036.

the concordance is everywhere deceptive, and that between the schists and the fossiliferous series of formations there is really a great hiatus.[71] When the fossil-bearing intercalations are examined they are themselves found to be metamorphosed. The Jurassic limestones have been marmarized, and the shales have become lustrous sericite-schists in which belemnites and other fossils are recognizable. The Triassic rocks have been in like manner rendered crystalline, and present Secondary crystals of albite, quartz, mica, tourmaline, garnet, etc. The Carboniferous strata, when their age can be determined by inclosed fossils, consist of dark anthracitic bands, which have undergone less alteration than the adjacent schists.[72] But the extraordinary way in which many of the plants in the Alpine Carboniferous rocks have been distorted indicates the enormous shearing which these rocks have undergone.[73] At Vernayaz, near Martigny, the Carboniferous strata can hardly be separated from the schists;[74] and, indeed, had Carboniferous plants not been found in them the idea would probably never have occurred to any one to draw a line between them. At the well-known locality of Petit Cœur, the plants so abundantly and admirably preserved in black schist have had their original substance replaced by a white hydrous mica.[75]

A detailed investigation of the geotectonic and petrographical relations of these intercalated Carboniferous bands was carried out in 1882 by the late Mr. Stur, Director of the Austro-Hungarian Geological Survey, and Baron von Foullon.[76] On the northern border of the Styrian Alps near Leoben a group of crystalline schists 10,000 to 13,000 feet

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[71] Professor Lory believed that in the Western Alps there is a conformability and even gradation between the true crystalline schists and the Palæozoic and Secondary rocks. He regarded the crystalline character of the latter as an original feature dating from the time of deposition. See his résumé in the Report of the London meeting, 1888, of the International Geological Congress, and the views of M. Michel-Lévy in the same Report.

[72] It is well known that carbonaceous strata can be recognized across zones of contact-metamorphism, when the normal characters of the ordinary strata above and below them have been destroyed. This is well seen in the case of the black graptolitic shales of the south of Scotland, and, still more strikingly, in those of Christiania. See Brögger's memoir cited on p. 1030.

[73] See Heer's "Flora Fossilis Helvetiæ" (Steinkohlen Flora), plate iv. fig. 1; v. figs. 1, 3; viii. figs. 1, 2; xiii. fig. 1, etc.

[74] Favre, "Recherches geol." ii. p. 351. The same fact is admitted by Lory to be often true elsewhere (Bull. Soc. Geol. France, ix. 1881, p. 653).

[75] Favre, op. cit. iii. p. 192.

[76] Jahrb. Geol. Reichsanst. xxxiii. 1883, pp. 189, 207. See also Toula, Verh. Geol. Reichsanst. 1877, p. 240.

thick reclines steeply (but it is said conformably) against gneiss. It consists of phyllite-gneiss, mica-schist, and chlorite-schist, with four bands of dark graphitic schist and one or two seams of limestone. The plant-bearing graphitic schist is full of plant-remains (*Calamites ramosus*, *Pecopteris lonchitica*, *Lepidodendron phlegmaria*, etc.). The association of plants and the occurrence of bands of graphite, representative doubtless of former beds of coal, indicate that these carbonaceous rocks belong to the well-known Schatzler group of the lower Coal-series of Silesia. The whole succession of schists of which these plant-bearing beds are members, forms one continuous group, which Stur recognized as traceable for a long distance on the northern margin of the central range of the northeastern Alps. He insisted that this group of schists cannot be the result of original chemical deposition, but, on the contrary, that it is shown, by a great series of facts, to be the metamorphosed equivalent of what, elsewhere, are unaltered Carboniferous strata. The distortion of the fossils, which proves that the rocks have behaved like plastic masses under the strain of mountain-making, the alteration of their substance into anthracite or graphite, and its replacement by micaceous silicates, are evidence of a serious metamorphism. On the other hand, the occurrence of unaltered plant-bearing Carboniferous rocks elsewhere in the Alps shows that, as usual, the metamorphism has not been everywhere equally intense. Stur concluded that there was every encouragement to search for fossils in the schist envelope of the central Alpine gneiss.[77]

Baron von Foullon describes the petrographical characters of the various members of the group of schists in which the plants occur near Leoben. As to the thoroughly crystalline character of the phyllite-gneiss, mica-schist, etc., there can be no dispute. It will be enough here to refer briefly to the constitution of the graphite-schist in which the plants occur. Hand-specimens present a dull fracture, on which none of the components, except the graphite, can be recognized, though sometimes they show a greenish fibrous asbestiform mineral. In thin slices, the rock is

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[77] He had, many years before this, announced his belief that the schistose envelope (Schieferhülle) of the Alps probably represents Palæozoic rocks. Stache, in 1874, wrote that "the question now is how far Cambrian or Silurian rocks are represented." Jahrb. Geol. Reichs. 1874, p. 159. In 1884 he thought that the epicrystalline condition of the Silurian rocks in the Alps might be due to original crystalline precipitation; Z. Deutsch. Geol. Ges. 1884, p. 356.

seen to be composed of quartz grains, chloritoid, an asbestos-like substance, and a mica, with abundant "clay-slate microlites," and diffused carbonaceous matter. It resembles the mica-chloritoid-schists of the Taunus. Some of the chloritoid-schists or quartz-phyllites associated with this plant-bearing band are also graphitic. Petrographical investigation thus concurs with the stratigraphical evidence to prove that a tract of the crystalline schists of the north-eastern Alps consists of metamorphosed Carboniferous rocks.

The Silurian rocks, which in the eastern Alps are graywacke and slate, become more and more crystalline as they are followed westward. The Liassic shales become micasized toward the central mountains, the fossils by degrees disappear, and the limestones, assuming a jointed aspect, finally pass into a completely crystalline condition. In the Vaud Alps, the belemnites of the middle Oxfordian shales gradually disappear in proportion as the rock becomes more schistose, till at the Diablerets it is an almost crystalline sericitic schist.[78] The Eocene strata, also, under intense compression, have assumed the character of slates, which are worked for economic purposes.[79]

So far, therefore, from being entirely a pre-Cambrian series, the crystalline schists of the Alps can be demonstrated to include metamorphosed Palæozoic and Secondary rocks along their outer border. How far toward the central mass of the mountains they are of Palæozoic age has yet to be determined. As the rocks become more and more crystalline in that direction it may not always be possible to define the base of the altered Palæozoic rocks. That there is a nucleus of ancient or "Archæan" gneisses is not disputed; but its limits must be proved by stratigraphical evidence.[80]

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[78] Renevier, Bull. Soc. Geol. France (3), ix. p. 650; xvii. 1889, p. 884.

[79] Lory, Bull. Soc. Geol. France, ix. 1881, p. 651.

[80] M. Vacek has shown an unconformability between the older central schists and the Silurian gneiss, diorite-schist, mica-schist and chloritoid-schist. Jahrb. Geol. Reichsanst. xxxiv. 1884, p. 620. The Palæozoic and Secondary age of part of the schists of the Alps is enforced by Heim, "Mechanismus der Gebirgsbildung," 1878; Compte Rend. Congrès Geol. International London, 1888, p. 16; Nature, xxxviii. 1888, p. 524; Quart. Journ. Geol. Soc. xlvi. 1890, p. 236. Grubenmann, Mittheil. Thurganischen Naturf. Gesellsch. Heft viii. 1888. Baltzer, "Beiträge zur Geol. Karte der Schweiz," No. 24, 1888. The volumes of these "Beiträge" contain ample details regarding the geological structure of the Alps. P. Termier, Comptes Rend. Acad. France, cxii. 1891, p. 900. Prof. Bonney holds that the crystalline schists of the Alps are older than the Palæozoic rocks. See, for example, his Address to the Geol. Soc. (Q. J. Geol. Soc. vol. xlii 1886, p. 66), and the same Journal for 1889, p. 67; 1890, p. 187; 1892, p. 390.

Scottish Highlands.—This region consists mainly of crystalline schists with bosses of granite, porphyry, etc., which, stretching through four degrees of latitude and four and a half of longitude, must cover an area of not less than 16,000 square miles at the surface. As, however, they sink beneath later formations, and are prolonged into Ireland, their total area must be still more extensive. The oldest rocks consist mainly of a remarkably coarse crystalline gneiss (Lewisian, 1 in Fig. 311), with abundant pegmatite veins, seen in Sutherland and Ross, the two north-westerly counties of Scotland. This gneiss, which will be described in the section on pre-Cambrian rocks in Book VI., is unconformably overlain by nearly flat brownish-red (Torridonian) sandstones, conglomerates and breccias (2), which in turn are surmounted unconformably by inclined beds of quartzite (3, 4), shales (5), calcareous grit (6), and limestones (7), the geological age of which is fixed by the occurrence of recognizable fossils in them. The quartzite is full of annelid-burrows; the shales contain *Olenellus*—the distinctive trilobite of the lowest Cambrian rocks; the limestone has yielded *Maclurea*, *Murchisonia*, *Ophileta*, *Pleurotomaria*, *Orthis*, *Orthoceras*, *Piloceras*, and many more forms, indicating Cambrian and possibly the very lowest Silurian horizons. The strata are generally crowded with carbonaceous worm-casts (the so-called "fucoids").

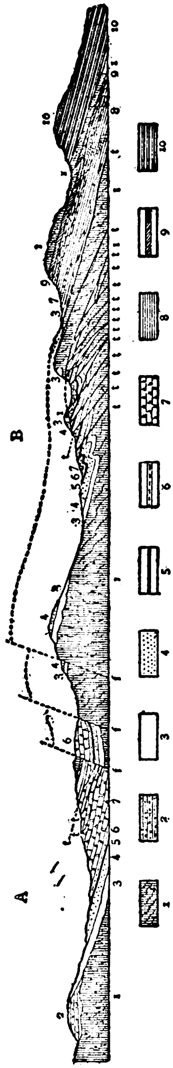

Fig. 311.—Diagram-section to show the geological structure of the Northwest of Scotland.

10. Gneissose Flagstones, etc. } NEWER OR EASTERN GNEISS ("MOINE SCHISTS").
9. Siliceous schist
8. { Frilled schist / Green schist

7. Durness-Eriboll Limestone } CAMBRIAN OR LOWER SILURIAN.
6. Serpulite Grit (*Salterella*)
5. Fucoid-Beds (*Olenellus*)
4. Piped Quartzite (*Annelids*) } CAMBRIAN.
3. { False-bedded Quartzite / Basal Breccia

2. Red Sandstones and Conglomerates } TORRIDON SANDSTONE.
1. Gneiss, Granite, Pegmatite, etc. } LEWISIAN GNEISS.

A, Durness Area; B, Eriboll Area; f f, Normal Faults; t t, Reversed Faults and Thrust-planes; Dotted lines, continuation of normal Faults and Thrust-planes.

Along their western margin, these rocks are so little altered that they do not in any way deserve the name of metamorphic. Eastward, however, they pass under various schists and gneisses (8, 9, 10), which form a vast overlying, thoroughly crystalline series. It was believed by Macculloch and Hay Cunningham that the fossiliferous beds truly underlie, and are older than, the eastern gneiss. This view was adopted and worked out in some detail by Murchison, who extended his generalization over the whole area of the Highlands, which he regarded as composed essentially of metamorphosed Silurian rocks (see Book VI., Part I. "Pre-Cambrian," § ii. "Local Development"). Other geologists supported Murchison, whose opinions met with general acceptance. Nicol, however, contended that the overlying or "newer gneiss" is merely the old gneiss brought up by faulting. Later writers, particularly Prof. Lapworth, Dr. Callaway and Dr. Hicks, advanced somewhat similar opinions; but the difficulty remained of explaining how, if the "newer gneiss" is really older than the fossiliferous strata, it should overlie them so conformably as to have deceived so many observers. The problem was subsequently attacked independently by Prof. Lapworth and by the Geological Survey, especially by Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman and H. M. Cadell, and I believe it has now been solved. I fully shared Murchison's belief in a continuous upward succession from the fossiliferous Lower Silurian strata into the overlying schists, but the subsequent detailed investigation of the ground convinced me that this belief could no longer be entertained.

Tracing the unaltered Cambrian strata eastward from where they lie in their normal position upon the Torridon sandstone and old gneiss below, we find them begin to undergo curvature. They are thrown into N.N.E. and S.S.W. anticlinal and synclinal folds which become increasingly steeper on their western fronts until they are disrupted, and the eastern limb of a fold is pushed over the western. By a system of reversed faults (t t in Fig. 311), a single group of strata is made to cover a great breadth of ground and actually to overlie higher members of the same series. The most extraordinary dislocations, however, are the Thrust-planes. These have so low a hade that the rocks on their upthrow side have been, as it were, pushed horizontally westward, in some places for a distance of at least ten miles. But for the evidence of the clear

coast-sections, these thrust-planes could hardly be distinguished from ordinary stratification-planes, like which they have been plicated, faulted and denuded (dotted lines in Fig. 311). Here and there an outlier of horizontally displaced Lewisian gneiss may be seen capping a hill of quartzite and limestone like an ordinary overlying formation.

The general trend of all the foldings and ruptures is N.N.E. and S.S.W., and as the steeper fronts of the folds face the west, the direction of movement has obviously been from the opposite quarter. That there has been an enormous thrust from the eastward is further shown by a series of remarkable internal rearrangements that have been superinduced upon the rocks. Every mass of rock, irrespective of lithological character and structure, is traversed by striated surfaces, which lie approximately parallel with those of the thrust-planes, and are covered with a fine parallel lineation running in a W.N.W. and E.S.E. direction. Along many zones near the thrust-planes, and for a long way above them, the most perfect shear-structure has been developed (Fig. 256). The coarse pegmatites in the gneiss have had their pink felspar and milky quartz crushed and drawn out into fine parallel laminæ, till they assume the aspect of a rhyolite in which fluxion-structure has been exceptionally well developed. Hornblende-rock passes into hornblende-schist. Sandstones, quartzites, and shales become finely micaceous schists. The annelid-tubes in the quartzite are flattened and drawn out into ribbons. New minerals, especially mica, have been abundantly developed along the superinduced divisional planes, and, in many cases, their longer axes are ranged in the same dominant direction from E.S.E. to W.N.W.

The whole of these rocks have undergone such intense shearing during their westward displacement that their original characters have in many cases been obliterated. Among them, however, can be recognized bands of gneiss which undoubtedly belong to the underlying Lewisian series. With these are intercalated lenticular strips of Cambrian quartzite and limestone. In some areas the Torridon sandstone has been heaped on itself, sheared, and driven westward in large slices, the sandstones passing into sericitic schists and the conglomerates having their pebbles flattened and elongated, while the matrix has become full of secondary mica. Eastward, above one of the most marked and persistent thrust-planes, the prevailing rock is a flaggy fissile micaceous gneiss or gneissose flagstone ("Moine schist,"

Book VI. Part I. § ii.). All these rocks have a general dip and strike parallel with those of the Cambrian strata on which they now rest, and in this respect, as well as in their prevailing lithological characters, they present the most striking contrast to the rocks that unconformably underlie the quartzites a little to the west. Whatever may have been their age and original condition, they have certainly acquired their present structure since Cambrian times.

From the remarkably constant relation between the dip of the Cambrian strata and the inclination of the reversed faults which traverse them, no matter into what various positions the two structures may have been thrown, it is tolerably clear that these dislocations took place before the strata had been seriously disturbed. The persistent parallelism of the faults, folds, and prevailing strike, indicates that the faulting and tilting were parts of one continuous process. The same dominant northeasterly trend governs the structure of the whole Highlands, and reappears over the Silurian tracts of the south of Scotland and north of England. If, as is probable, it is the result of one great series of terrestrial movements, these must have occurred between the middle or close of the Cambrian period and that portion of the Old Red Sandstone period represented by the breccias and conglomerates of the Highlands. When the rocks were undergoing this metamorphism, there lay to the northwest a solid ridge of old gneiss and Torridon sandstone which offered strong resistance to plication. The thrust from the eastward against this ridge must have been of the most gigantic kind, for huge slices, hundreds of feet in thickness, were shorn off from the quartzites, limestones, red sandstones, and gneiss, and were pushed for miles to the westward. During this process, all the rocks driven forward by it had their original structure more or less completely effaced. New planes, generally parallel with the surfaces of movement, were developed in them, and along these new planes a rearrangement and recrystallization of mineral constituents took place, resulting in the production of crystalline schists.[81]

Much remains to be done before the structure of the Central and Southern Highlands is explained. That some portions of the rocks may belong to the Lewisian gneiss is not improbable. But, on the other hand, in almost all parts of

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[81] Nature, xxxi. p. 30; Quart. Journ. Geol. Soc. xliv. 1888, p. 378. For further details see the account of pre-Cambrian rocks in Book VI. Part I. § ii.

the Highlands east of the Great Glen traces of an original fragmental or clastic origin can be detected among the schistose rocks. Zones of argillaceous shales or slates passing into andalusite-slates,[82] and of fine grit full of well-rounded fragments of quartz, felspar, or other ingredient, occur. Bands of coarse conglomerate lie on different horizons, the pebbles (granite, gneiss, etc.) being enveloped in a schistose matrix. Microscopic investigation likewise reveals, even among crystalline mica-schists, traces of the original water-worn granules of quartz in the sandy mud out of which the rocks have been formed. It is deserving of remark that the rocks along the southern margin of the Highlands are, for the most part, so little affected as closely to resemble portions of the unaltered Silurian series of the south of Scotland, and that they dip toward the mountains, becoming more highly foliated and crystalline as they recede from the lowlands. It is also noteworthy that zones of graphitic schist can be traced through different tracts of the Highlands, and that these schists and their associated strata bear a close resemblance to the carbonaceous bands associated with sedimentary deposits, such, for instance, as the Silurian anthracitic graptolite zones of the southern counties.[83]

Various eruptive rocks traverse the Highland schists, and afford interesting studies in their relation to the problems of metamorphism. Thus in Banffshire and Aberdeenshire, large masses of diorite, diabase, and gabbro cut the schists in places, but run on the whole parallel with the general strike of the region. Their appearance, though later than that of the rocks through which they have come, was earlier than the regional metamorphism. The diorite has, in many places, itself undergone great alteration. Its component crystals have ranged themselves in the direction of

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[82] It is important to note, as showing the relation of regional to contact-metamorphism, that every stage in the development of the andalusite can be traced in these slates, though no eruptive rock appears at the surface. J. Horne, Mineral. Mag. 1884. I have proposed to class the metamorphic rocks of the Central and Southern Highlands by the name of Dalradian, for convenience of reference until their true geological position shall have been determined. Address to Geol. Soc., Quart. Journ. Geol. Soc. 1891, p. 75, and postea, Book VI. Part I. § ii.

[83] Among the less metamorphosed rocks that form the southern margin of the Highlands some zones of graphitic schist, together with chert bands and courses of igneous rocks, wonderfully remind the geologist of the similar assemblage of rocks in the south of Scotland. As this sheet is passing through the press Mr. Peach has detected radiolaria in these cherts, occurring much in the same way as they do in the radiolarian cherts of the southern uplands.

the prevalent foliation, and have here and there separated into distinct aggregates, the felspar forming a kind of labrador-rock, and the hornblende assuming the structure of perfect hornblende-schist. Numerous bosses of granite and porphyries likewise occur, traversing the diorites and schists and therefore of still later date. In the course of the Geological Survey of the Southern Highlands Mr. G. Barrow has found evidence that over and above the effects of great dynamical movements affecting wide tracts of country, a marked amount of metamorphism may be traced to the influence of eruptive granites and gneisses. He shows that a vast number of pegmatite veins which traverse the schists may be traced into bosses of intrusive granite or gneiss, the great mass of which is concealed below ground. He finds that three well-marked zones can be observed in the schists, of which the first, lying nearest to the main body of eruptive material, is marked by an abundance of sillimanite, the next by kyanite, and the outermost by staurolite. He has followed the same band of altered sedimentary material across these zones which are thus shown to be entirely independent of the original structure of the rocks. These observations, which have been extended over many hundred square miles of Forfarshire, Perthshire, and Aberdeenshire, are of much interest and importance, as they serve to connect the phenomena of contact and regional metamorphism as manifestations of one great process.[84]

Greece.—In the Grecian peninsula, vast masses of chlorite-schist, mica-schist, and gneiss occur, among which thick zones of marble are interstratified. At several places in the calcareous zones fossils have been found which, though not well preserved, show that the rocks belong to the fossiliferous series of formations, and are not pre-Cambrian. These crystalline rocks in northeastern Greece lie on the strike of normal Cretaceous hippurite limestones, sandstones, and shales, and are probably of Cretaceous age.[85]

Green Mountains of New England.—The Lower Silurian strata, which to the north in Vermont are comparatively little changed, become increasingly altered as they are traced southward into New York Island. They

[84] G. Barrow, Quart. Journ. Geol. Soc. 1893.

[85] M. Neumayr, Jahrb. Geol. Reichsanst. xxvi. 1876, p. 249. Z. Deutsch. Geol. Ges. xxxiii. pp. 118, 454. A. Bittner, M. Neumayr, and F. Teller, Denksch. Akad. Wien, xl. 1880, p. 395. This essay well deserves the attention of the student.

are thrown into sharp folds, and even inverted, the direction of plication being generally N.N.E. and S.S.W. This disturbance has been accompanied by a marked crystallization. The limestones have become marbles, the sandy beds quartzites, and the other strata have assumed the character of slate, mica-schist, chlorite-schist, and gneiss, among which hornblendic, augitic, hypersthenic, and chrysolitic zones occur. The geological horizon of these rocks is shown by the discovery in them at various localities of fossils belonging to the Trenton and Hudson River subdivisions of the Lower Silurian system of eastern North America. The rocks have been ridged up and altered along a belt of country lying to the east of the Hudson and extending north into Canada.[86]

Menominee and Marquette regions of Michigan.—One of the most luminous essays yet published on the megascopic and microscopic proofs of dynamic metamorphism is that by G. H. Williams to which reference has already been made.[87] The author proves that a series of pre-Cambrian rocks of eruptive origin (greenstones, tuffs, agglomerates, etc.) have been converted into perfect schists. The various stages of alteration are minutely detailed, and careful drawings are given of the microscopic structures. The deductions arrived at by the author have far more than a mere local significance; they lay an accurate basis for the study of similar "greenstone-schists" in other regions, and show how the original eruptive character of such altered rocks is to be recognized.

It may be useful to group the foregoing and a few other examples of regional metamorphism in stratigraphical order, that the student may see over how wide a range of the geological formations such transformation has taken place.

Tertiary.—Northern and Central Italy.—Nummulitic limestone rendered saccharoid, and strata (including Miocene) generally more indurated in proportion to the extent to which they have been folded and disturbed. These changes, which indicate an incipient

[86] See Dana, Amer. Journ. Sci. iv. v. vi. xiii. xiv. xvii. xviii. xix. xx.; Q. J. Geol. Soc. 1882, p. 397. The identification of the so-called Taconic schists of New England with altered Lower Silurian rocks has been called in question by Sterry Hunt, but the stratigraphical evidence collected by A. Wing, Dana and others, and the testimony of the fossils collected by Dana, Dwight, etc., have sustained it. In the Punjab a series of gneisses and schists overlies infra-Triassic rocks. Wynne, Geol. Mag. 1880, p. 314.

[87] Bull. U. S. Geol. Survey, No. 62, 1890.

metamorphism, are well displayed in the Apuan Alps and in the Apennines.[88]

Cretaceous.—Greece.—Chlorite-schist, mica-schist, marble, serpentine, etc., believed to be altered Cretaceous sandstone, shale, limestone, etc. (see above).

Coast range of California.—Strata containing Cretaceous fossils pass into jaspers, siliceous slate (phthanites), glaucophane-schist, garnetiferous mica-schist, serpentine, etc.[89]

Jurassic.—Alps.—Sericite-schists, altered limestones, etc. (p. 1033).

Sierra Nevada (California).—Clay-slates, talcose slates, serpentine, etc., passing into rocks containing Jurassic fossils.[90]

Trias.—Sierra Nevada (Spain).—Clay-slate, mica-schists, talc-schists, and limestones.[91]

Carrara.—Mica-schist, talc-schist, marbles, passing down into limestones containing *Encrinus liliiformis*, *Phylloceras*, *Pentacrinus*, below which lie gneissic and other schists inclosing *Orthoceras*, *Actinoceras*, and evidently of Palæozoic age.[92]

Alps.—Limestones, dolomites, and gypsums rendered crystalline, associated with calc-mica-schist and other varieties of schist.

Carboniferous.—Alps. — Graphite-schist, phyllite-gneiss, etc. (p. 1033).

Eastern Brittany.—Carboniferous shales altered into crystalline schists.[93]

Devonian.—Taunus.—A large series of crystalline schists (p. 1030).

Ardennes.—Crystalline schists with garnet, hornblende, mica, etc. (p. 1028).

Silurian.—Norway.—A series of schists resembling those

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88 Lotti and Zaccagna, Boll. Comit. Geol. d'Italia, 1881, p. 5. Lotti, ibid. p. 419, Bull. Soc. Geol. France, xvi. 1888, p. 406.

89 Whitney, Geol. Surv. California, "Geology," vol. i. p. 23. G. F. Becker, Amer. Journ. Sci. xxxi. 1886, p. 348; "Geology of the Quicksilver Deposits of the Pacific Slope," Monograph No. xiii. of U. S. Geol. Survey, 1888.

90 Whitney, op. cit. p. 225.

91 De Verneuil, Bull. Soc. Geol. France (2), xiii. p. 708. R. von Drasche, Jahrb. Geol. Reichsanst. xxix. 1879, p. 93. The identification of these rocks with Triassic beds is a probable conjecture.

92 Coquand, Bull. Soc. Geol. France (3), iii. p. 26; iv. p. 126. Zaccagna, Boll. Com. Geol. Ital. xii. 1881, p. 476. Lotti, op. cit. p. 419 and plate ix.

93 Jannettaz, Bull. Soc. Geol. France (3), ix. 1881, p. 649.

of Scotland, lying upon and interstratified with fossiliferous beds (p. 1031).

Green Mountains of New England.—A great group of schists and limestones, with fossils in some beds (p. 1041).

Northern Alps.—Upper Silurian fossils among gneiss, diorite-schist, mica-schist, chloritoid-schist, etc.[94]

Cambrian and Silurian.—Scotland.—A great series of crystalline schists overlying quartzite and limestones with fossils (p. 1035).

Saxon granulite tract.—Schists, schistose conglomerates, etc.[95]

South Wales.—A fine foliation of the tuffs, representing an early stage of regional metamorphism.[96]

Pre-Cambrian (Archæan).—Scotland. — Sandstone and arkose passing into lustrous crumpled micaceous schists (p. 905). Some of the Archæan gneisses and hornblende-rocks of Sutherland have had a new schistosity superinduced in them by the shearing movements that altered the Cambrian strata (p. 1040).

Summary.—From the evidence now adduced the following conclusions may be confidently drawn.

1. There are wide regions in which crystalline schists (*a*) overlie fossiliferous strata, or (*b*) contain intercalated bands in which fossils occur, or (*c*) pass either laterally or vertically into undoubted sedimentary strata.

2. These schists are in some cases the metamorphosed equivalents of what were once ordinary sedimentary deposits, including sometimes associated igneous rocks..

3. The alteration by which rocks have been affected in regional metamorphism is similar in its stages to what may be traced in local metamorphism round bosses of granite, but has attained a much greater development.

4. Regional metamorphism has been directly connected

[94] M. Vacek and Baron Foullon, Jahrb. Geol. Reichsanst. xxxiv. 1884, pp. 609, 635. G. Stache, Z. Deutsch. Geol. Ges. 1884, p. 277.

[95] Lehmann's work cited ante, p. 272.

[96] Q. J. Geol. Soc. xxxix. 1883, p 310.

with intense compression or tension, and is usually most pronounced where, as shown by plication, puckering, shear-structure, and the crushing down of the component minerals, the rocks have been subjected to the greatest mechanical movement.

5. The dynamical strain has been generally, perhaps always, accompanied with more or less chemical reaction, not, as a rule, involving the introduction of new chemical constituents, but consisting chiefly in a recombination of those already present in the rocks, with the consequent development of new crystalline minerals.

6. This chemical and mineralogical rearrangement has probably been superinduced under the influence of moderate heat, and in presence of water, and is comparable with what, on a feeble scale, can be achieved in the laboratory.

7. The alteration of rocks in an area of regional metamorphism is often strikingly unequal in degree even over limited areas, being apt to attain sporadically a maximum intensity, particularly in tracts of greatest shearing or plication, while in other areas the original clastic or crystalline characters may be easily discernible.

8. The nature of the alteration has depended first, and chiefly, on the original character and structure of the rocks affected by it; and secondly, on the nature and intensity of the metamorphic activities. Of some rocks (sandstone, carbonaceous shale, coal), the original condition may be recognizable when that of their associated strata has entirely disappeared.

9. The foliation in a tract of regional metamorphism has been developed along divisional planes which guided the crystallization or rearrangement of the minerals. In some cases, these planes coincide with those of original deposit.

In others, they may represent cleavage, as pointed out by Sedgwick and Darwin. Or they may indicate the planes along which, under intense pressure, the longer axes of crystallizing minerals would naturally range themselves. In a rock, homogeneous in chemical composition and general texture, foliation might be induced along any dominant divisional planes. If these planes were those of cleavage or of shearing, the resultant foliation might not appreciably differ from that along original bedding planes.[97] But it may be doubted whether a cleavage foliation of clastic sedimentary strata could run over wide areas without sensible and even very serious interruptions. In most large masses of sedimentary matter, the usual alternations of different kinds of sediment could not but produce distinct kinds of rock under the influence of metamorphic change. Where foliation coincides with cleavage over large tracts, it will almost certainly be crossed by bands, more or less distinct, coincident with the original bedding whether of sedimentary or of eruptive rocks, and running oblique to the general foliation, as bedding and cleavage do, save where they may happen to coalesce. Where a massive rock of generally homogeneous composition, such as a felsite or granite, has been intensely sheared, a rearrangement or recrystallization of its minerals has taken place along the planes of shearing. Such a rock is thus transformed into a schist. Even rocks of much more varied structure, like Archæan gneisses, have been subjected to such changes from shearing as not only to lose entirely their original structure, but to acquire a new foliation parallel to the shearing planes.

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[97] Jannettaz points out that the cleavage of the slates in the Grenoble Alps is parallel to the foliation of the mica-schists. Bull. Soc. Geol. France (3), ix. 1881, p. 649.

It is now generally agreed that gneisses and many forms of schist have been formed by dynamical action from deep-seated masses of igneous rocks, both acid and basic. The banding of these rocks, which was formerly regarded as evidence of aqueous deposition, is no doubt generally due to an original segregation of the component minerals of still unconsolidated igneous rocks, like the segregation-veins described on p. 963, though it may to some extent have resulted from the rearrangement and recrystallization of the materials of such rocks under intense mechanical strain. The occurrence of lenticular bands or bosses of amphibolite in gneiss may point to dikes of some hornblendic rock by which the original granite was traversed before the development of the foliated structure. A smiliar connection can be traced between masses of diorite, gabbro, etc., and hornblende-schists, gabbro-schists, etc. The granitoid character of these rocks, under the great stresses they have suffered during periods of terrestrial disturbance, has here and there entirely disappeared. First the minerals (especially the felspars) are seen to have ranged themselves with their long axis in one general direction. Then they separate into layers or folia in the same direction, and acquire a more or less distinctly foliated structure. Thus, a massive diorite, gabbro, or diabase has been converted into amphibolite-schist, sometimes with bands of massive labradorite.[98]

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[98] The idea suggested many years ago by Jukes ("Student's Manual of Geology"), that the hornblendic bands of the crystalline schists might have been originally eruptive rocks, has been confirmed by more recent work. See Lehmann's "Entstehung der altkrystallinischen Schiefergesteine"; Allport, Q. J. Geol. Soc. xxxii. 1876, p. 425; the diorites of the north of Scotland, ante, p. 1040, and paper by G. H. Williams, cited on p. 1024.

Besides the works already cited on Metamorphism the student may consult the following: Delesse, Mem. Savans Étrangers, xvii. Paris, 1862, pp. 127–222; Ann. des Mines. xii. 1857; xiii. 1858; "Études sur le Métamorphisme des Roches," Paris, 1869; Durocher, "Études sur le Métamorphisme des Roches,"

PART IX. ORE DEPOSITS[1]

Metallic ores and other minerals that are extracted for their economic value occur in certain well-marked forms which have been variously classified; but for the purposes of the geological student it is most convenient to consider them from the point of view of geological structure and history. Thus arranged, they naturally group themselves into three great series; 1st, those contemporaneously deposited among stratified formations; 2d, those contemporaneously formed with the other ingredients of crystalline (massive and schistose) rocks; 3d, those subsequently introduced by infiltration or otherwise into fissures, caverns, or other spaces of any kind of rock.

1. Contemporaneous ores of stratified rocks have been deposited in water, together with the sandstones, limestones, or other strata among which they lie. In some cases, they are mere mechanical sediments, such as the auriferous gravels of California and Australia (placer-works) or

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Bull. Soc. Geol. France (2), iii. 1846; Daubrée, Ann. des Mines, 5me serie, xvi. p. 155; Bischof, "Chemical Geology," chap. xlviii.; J. Roth, Abhandlungen Akad. Berlin, 1871; 1880; Gümbel, "Oestbayerische Grenzgebirge," 1868; H. Credner, Zeitsch. Gesammt. Naturwiss. xxxii. 1868, p. 353; N. Jahrb. 1870, p. 970; A. Inostranzeff, "Studien über metamorphosirte Gesteine," Leipzig, 1879.

[1] The best English work on this subject is "Ore Deposits," by J. A. Phillips, 1884. The following works on ores and mining may also be consulted: B. von Cotta, "Die Lehre von Erzlagerstätten," 1859–61; A. von Groddeck, "Die Lehre von den Lagerstätten der Erze," 1879; W. Forster, "Treatise on a Section of the Strata from Newcastle-on-Tyne to Cross Fell"; W. Wallace, "Laws which regulate the deposition of Lead Ores," 1861; F. von Sandberger, "Untersuchungen über Erzgänge"; numerous valuable papers by J. W. Henwood and others in Trans. Roy. Geol. Soc. Cornwall; G. F. Becker, "Geology of the Comstock Lode," U. S. Geol. Survey, Monographs iii. iv.; also "Quicksilver Deposits," 8th Ann. Rep. U. S. Geol. Survey, 1886–87, p. 965, and Monograph xiii.; R. D. Irving, "Copper-bearing rocks of Lake Superior," Ann. Rep. U. S. Geol. Survey, 1881–82, p. 93 and Monograph v.; "Gîtes Minéraux," E. Fuchs et L. Delaunay, Paris, 1893.

the stream-tin deposits of Cornwall, obviously derived from the disintegration of older rocks, principally veinstones, in which the ores were developed. In other cases, they result from the accumulation of chemical precipitates, as in the modern deposition of iron-ore on the floors of lakes and beneath bogs. These precipitates may either of themselves form independent mineral masses, or may serve as impregnations of other stratified deposits, like the copper ores that occur so abundantly diffused through the Kupfer-Schiefer of Saxony. In all these instances, the metalliferous rocks belong to the stratified type of geological structure (p. 834 *et seq.*). They occur in layers varying from mere films up to beds or stratified masses of great thickness. In some cases, they retain the same average thickness for long distances; in others, they swell out or die away rapidly, or occur in scattered concretions. Organic remains are commonly associated with ores of this type.

2. Contemporaneous ores of crystalline rocks are exemplified by the beds of iron-ore, pyrites, etc., that so frequently occur intercalated among the crystalline schists. They lie as massive sheets or thin partings, and usually present a conspicuously lenticular character. That they were formed contemporaneously with the layers of quartz, mica, felspar, hornblende, or other minerals among which they lie, and owe their crystalline structure to the same process that produced the characteristic foliation of the crystalline schists, may usually be inferred with considerable certainty, though cases not infrequently arise where it is difficult or impossible to draw any line between this type and that of true subsequently-formed veins. Besides these lenticular ores of the crystalline schists, the massive rocks also contain contemporaneously crystallized ores. The diffused

magnetite and titaniferous iron of the basalts, diabases, etc., and the occasional separation of the ore in the layers of segregation-veins in these rocks are familiar illustrations. Large included masses of these and other ores are sometimes available for mining (ante, p. 129).

3. Subsequently introduced ores are distinguished by the contrast between their contents and structure and those of the rocks through which they pass. They have been deposited, subsequent to the consolidation of these rocks, in cavities previously opened for their reception. In certain rocks (limestones, dolomites, etc.) intricate channels and large irregular caverns have been dissolved out by the solvent action of underground water; in other cases, fissures have been formed by fracture, or the rocks, exposed to great compression, have been puckered up or torn asunder, so that irregular spaces have been opened in them. Metallic ores and crystalline minerals introduced by infiltration, sublimation, or otherwise, into the cavities formed in any of these ways, may be grouped, according to the shape of the cavity, into veins or lodes, which have filled up vertical or highly-inclined fissures, and stocks, which are indefinite aggregations often found occupying the place of subterranean cavities.

The first two of these three types of ore deposits do not require special treatment here. The stratified type has the usual character of sedimentary formations (Book IV. Part I.); the crystalline type forms part of the structure of schistose and massive rocks (Book II. Part II. Sect. vii. §§ 2 and 3; and Book VI. Part I. § i.); the third type, however, from its economic importance and its geological interest, merits some more detailed notice.

§ i. Mineral-Veins or Lodes

A true mineral-vein consists of one or more minerals deposited within a fissure of the earth's crust, and is usually inclined at from 10° to 20° from the vertical. The bounding surfaces of such a vein are termed walls, and, where inclined, that which is uppermost is known as the *hanging*, and that which is lowest as the *lying* or *foot* wall. The surrounding rock, through which veins run, is termed the country or country-rock. A vein may coincide with a line of fault or of joint, or may run independent of any other structural divisions; in all cases it is independent of the bedding or foliation of the "country." Cases occur among crystalline massive rocks, however, and still more frequently among limestones, where the introduction of mineral matter has taken place along gently inclined or even horizontal planes, such as those of stratification, and the veins then look like interstratified beds. Mineral-veins are composed of masses or layers of simple minerals or metallic ores alternating, or more irregularly intermingled with each other, distinct from the surrounding rock, and evidently the result of separate deposition. They are in no respect to be confounded with veins of rock injected in a molten condition from below, or segregated from a surrounding pasty magma into cracks in its mass. But they are commonly most frequent and most metalliferous in districts where eruptive rocks are abundant.

Variations in breadth.—Mineral-veins vary in breadth from a mere paper-like film up to a great wall of rock 150 feet wide or more. The simplest kinds are the threads or strings of calcite and quartz, so frequently to be observed

among the more ancient, and especially more or less altered, rocks. These may be seen running in parallel lines, or ramifying into an intricate network, sometimes uniting into thick branches and again rapidly thinning away. Considerable variations in breadth may be traced in the same vein. These may be accounted for by unequal solution and removal of the walls of a fissure, as in the action of permeating water upon a calcareous rock; by the irregular opening of a rent, or by a shift of the walls of a sinuous or irregularly defined fissure. In the last-named case, the vein may be strikingly unequal in breadth, here and there nearly disappearing by the convergence of the walls, and then rapidly swelling out and again diminishing. How simply this irreg-

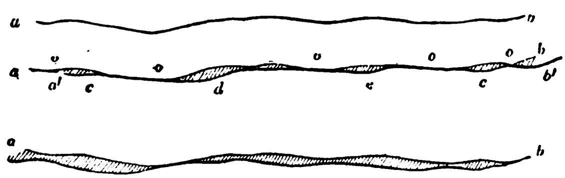

Fig. 312.—Widening of a fissure by relative shifting of its side (De la Beche).

ularity may be accounted for will be readily perceived by merely copying the line of such an uneven fissure on tracing paper and shifting the tracing along the line of the original. If, for example, the fissure be assumed to have the form shown at *a b*, in the first line (Fig. 312), a slight shifting of one side to the right, as at *a′ b′* in the second line, will allow the two opposite walls to touch at only the points *o o*, while open spaces will be left at *c c d*. A movement to the same extent in the reverse direction would give rise to a more continuously open fissure, as in the third line. That shiftings of this nature have occurred to an enormous extent in the fissures filled with mineral-veins, is shown

by their abundant slickensides (p. 878). The polished and striated walls have been coated with mineral matter, which has subsequently been similarly polished and grooved by a renewal of the slipping.

Structure and contents.—A mineral-vein may be either simple, that is, consisting entirely of one mineral, or compound, consisting of several; and may or may not be metalliferous. The minerals are usually crystalline, but layers or irregular patches of soft decomposed earth, clay, etc., frequently accompany them, especially as a layer on the wall-face (*flucan*). The non-metalliferous minerals are known as gangue or vein-stones, the more crystalline being often also popularly classed as spars. The metal-bearing minerals are known as ores. The commonest vein-stones are quartz (usually either crystalline or crypto-crystalline, with numerous fluid-inclusions), calcite, barytes, and fluorite. The presence of silica is revealed not only by the quartz, but by the hard siliceous bands so often observable along the walls of a vein. These can often be determined to be portions of the "country" which have been indurated by the deposition of silica in their pores. The ores are sometimes native metals, especially in the case of copper and gold; but for the most part are oxides, silicates, carbonates, sulphides, chlorides, or other combinations. Some of the contents of mineral-veins are associated with certain minerals more usually than with others, as galena with blende, pyrite with chalcopyrite, gold with quartz, magnetite with chlorite. Of the manner in which the contents of a mineral-vein are disposed the following are the chief varieties.

(1) Massive.—Showing no definite arrangement of the contents. This structure is especially characteristic of veins

consisting of a single mineral, as of calcite, quartz, or barytes. Some metalliferous ores (pyrites, limonite) likewise assume it.

(2) Banded, comby, in parallel (and sometimes exactly duplicated) layers or combs. In this common arrangement, each wall (*a a*, Fig. 314) may be coated with a layer of the same material, perhaps some ore or flucan (*b b*), followed on the inside by another layer (*c c*), perhaps quartz, then by layers of calcite, fluor-spar, or other vein-stone, with strings or layers of ore, to the centre, where the two opposite walls may be finally united by the last zone of deposit (*i*). Even where each half of the vein is not strictly a duplicate of the other, the same parallelism of distinct layers may be traced.

(3) Brecciated, containing angular fragments of the surrounding "country," cemented in a matrix of vein-stones

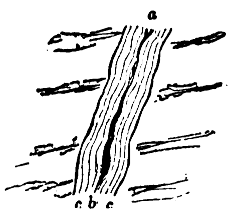

Fig. 313.—Section of a fissure nearly filled with one mineral (*c c*), but with a portion of the fissure (*a b*) still open.

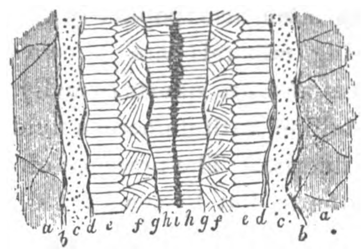

Fig. 314.—Section of Mineral-Vein with symmetrical disposition of duplicate layers.

or ores. It may often be observed that these fragments are completely inclosed within the matrix of the vein, which must have been partially open, with the matrix still in course of deposit, when they were detached from the parent rock. Large blocks (*riders*) may be thus inclosed.

(4) Drusy, containing or made up of cavities lined with crystalline minerals. The central parts of veins frequently present this structure, particularly where the minerals have been deposited from each side toward the middle.

(5) Filamentous, having the minerals disposed in thread-like veins; this is one of the commonest structures.

Metallic ores occur under a variety of forms in mineral-veins. Sometimes they are disseminated in minute grains or fine threads (gold, pyrites), or gathered into irregular strings, branches, bunches, or leaf-like expansions (native copper), or disposed in layers alternating with the vein-

stones parallel with the walls of the vein (most metallic ores), or forming the whole of the vein (pyrites, and occasionally galena), or lining drusy cavities, both on a small scale and in large chambers (hæmatite, galena). Some ores are frequently found in association (galena and blende), or are noted for containing minute proportions of another metal (argentiferous galena, auriferous pyrites).

Successive infilling of veins.—The symmetrical disposition represented in Fig. 314 shows that the fissure had its two walls coated first with the layers *b b*. Thereafter the still open, or subsequently widened, cleft received a second layer (*c c*) on each face, and so on progressively until the

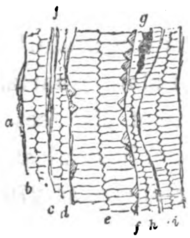

Fig. 315.—Section of Wheal Julia Lode, Cornwall, showing five successive openings of the same fissure (*B.*).
a f f, Copper-pyrites and blende; *b*, *d*, *e*, *h*, *i*, quartz in crystals pointing inward; *c*, clay; *g*, empty space.

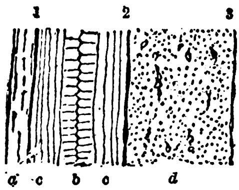

Fig. 316.—Section of part of a Lode, Godolphin Bridge, Cornwall (*B.*).
a, Quartz coating cheek of vein; *b*, quartz-crystals pointing inward; *c c*, agatiform silica; *d*, thick layer of copper-pyrites.

whole was filled up, or until only cavernous spaces (druses) lined with crystals were left. In such cases, no evidence exists of any terrestrial movement during the process of successive deposition. The fissure may have been originally as wide as the present vein, or may have been widened during the accumulation of mineral matter, so gradually and gently as not to disturb the gathering layers. But in many instances, as above stated, proofs remain of a series of disturbances whereby the formation of the vein was accelerated or interrupted. Thus at the Wheal Julia Lode,

Cornwall, the central zone (*e* in Fig. 315) is formed of quartz-crystals pointing as usual from the sides toward the centre of the vein, but it is only one of five similar zones, each of which marks an opening of the fissure and the subsequent closing of it by a deposit of mineral matter along the walls.[2] The occurrence of different layers on the two walls of a vein may sometimes indicate successive openings of the fissure. In Fig. 316 the fissure at one time, no doubt, extended no further than between 1 and 2. Whether the band of copper pyrites had already filled up the fissure, previous to the opening which allowed the deposit of the silica, or was introduced into a fissure opened between 2 and 3 after the deposit of the silica, is uncertain.[3]

The occurrence of rounded pebbles of slate, quartz, and granite in the lodes of Cornwall at depths of 600 feet from the surface, of gneiss in the vein at Joachimsthal at 1150 feet, and of Liassic land and freshwater shells at 270 feet in veins traversing the Carboniferous Limestone of the Mendip Hills and South Wales, seems to indicate that fissures may remain sufficiently open to allow of the introduction of water-worn stones and terrestrial organisms from the surface even down to considerable depths.[4]

Connection of veins with faults and cross-veins.—While the interspaces between any divisional planes in rocks may serve as receptacles of mineral depositions, the largest and most continuous veins have for the most part been formed in lines of fault. These may be traced, sometimes in a nearly straight course, for many miles across a country, and as far downward as mining operations have been able

[2] De la Beche, "Geol. Obs." p. 698. [3] De la Beche, op. cit. p. 699.
[4] De la Beche, op. cit. p. 696. Moore, Q. J. Geol. Soc. xxiii. 483; Brit. Assoc. 1869, p. 360.

to descend. Sometimes veins are themselves faulted and crossed by other veins. Like ordinary faults, also, they are apt to split up at their terminations. These features are well exhibited in some of the mining districts of Cornwall (Fig. 317).

The intersections of mineral-veins do not always at once

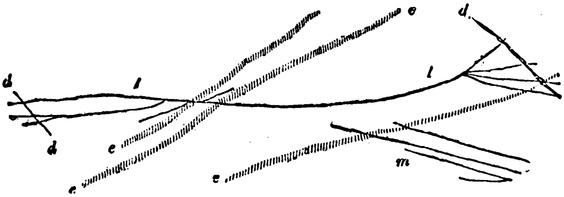

Fig. 317.—Plan of Wheal Fortune Lode, Cornwall (*B.*).
l l m, lodes of which the main one splits up toward east and west, traversing elvan dikes, *e e*, but cut by faults or cross-courses, *d d*. Scale one inch to a mile.

betray which is the older series. If a vein has really been shifted by another, it must of course be older than the latter. But the evidence of displacement may be deceptive. In such a section as that in Fig. 318, for example, a cursory examination might suggest the inference that the vein *d e* must be later than the dike or vein *a b*, by which its course appears to have been shifted. Should more careful scrutiny, however, lead to the detection of the vein crossing the supposed later mass at *c*, it would be clear that this inference must be incorrect.[5] In mineral districts, different series or systems of mineral-veins can generally be traced, one crossing another, belonging to different periods, and not infrequently filled with different ores and vein-stones. In the southwest of England, for example, a series of fissures run-

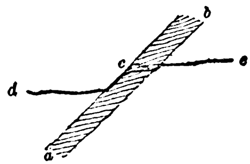

Fig. 318.—Deceptive shifting of a vein (*B.*).

[5] De la Beche, op. cit. p. 657.

ning N. and S., or N.N.W. and S.S.E., traverses another series, which runs in a more east and west direction (W.S.W. to E.N.E., or W.N.W. to E.S.E.). The latter (*c c*, *d d*, Fig. 319) in Cornwall contain the chief copper and tin ores, while the cross-courses (*b b*) contain lead and iron. The east and west lodes in the west part of the region were formed before those which cross them, for they are shifted, and their contents are broken through by the latter. To the east, near

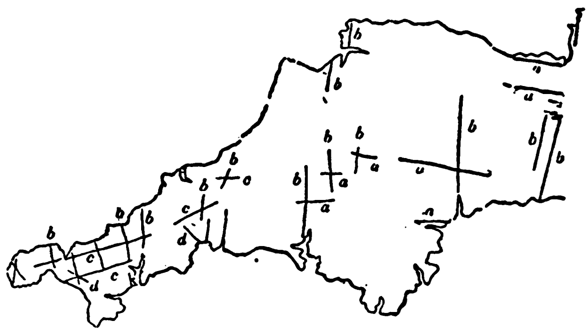

Fig. 319.—General Map of Fissures in the mineral tracts of S.W. England (*B.*).

Exeter, the east and west faults *a a* are later than the New Red Sandstone, and in Somerset than the Lias.[6]

Relation of contents of veins to surrounding rock.—It has long been familiar to miners that where a vein traverses various kinds of "country" it is often richer in ore when crossing or touching some rocks than others. In the north of England, for example, the galena is always most abundant in the limestones and scarcest in the shales, the veins in the Great Limestone (which is 150 feet thick or less) having produced as much lead as all the rest of a mass of 2000 feet of strata put together. In Cornwall and Devon, it has been observed that some lodes yield tin where they cross

[6] De la Beche, op. cit. p. 659.

granite, and copper where they traverse slate; the same lode, as at Botallack, may cross three times from the one rock into the other, and each time the same change of metallic contents takes place. Some of the lodes, which are poor in ore in the slate, become rich as they cross an elvan (Fig. 320), or, on the other hand, the ore is so split up into strings in the elvan, as to be much less valuable than in the slate. Similar variations in the nature or amount of ores and vein-stones with the character of the rocks traversed by mineral-veins have been generally observed in mining districts, even among the most diverse geological formations. Chemical analysis has revealed the presence of minute quantities of metallic ores dispersed through the substance of the rocks surrounding mineral-veins. By isolating some of the more frequent silicates found as rock-constituents (such as augite, hornblende, and mica), iron, nickel, copper, cobalt, arsenic, antimony, tin, etc., have been found in appreciable quantity, and the conclusion has been drawn by F. Sandberger that the heavy metals are present in the silicates of the crystalline rocks of all geological periods. Stratified rocks also, when subjected to sufficiently delicate analysis, reveal the presence in them of the metals and non-metallic substances that constitute mineral-veins. Clay-slates, for example, have been found to contain copper, zinc, lead, arsenic, antimony, tin, cobalt, nickel.[7]

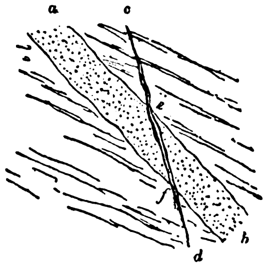

Fig. 320.—Plan of Elvan Dike (*a b*) traversed by a metallic vein (*c e f d*), which dies out as it passes into the surrounding slate, Wheal Alfred, Guinear (*B.*).

Decomposition and recomposition in mineral-veins.—It has

[7] This question has been made the subject of an exhaustive research by Prof. F. Sandberger, "Untersuchungen über Erzgänge," Part i.

been noticed that the "country" through which mineral-veins run is often considerably decomposed. In Cornwall, this is specially observable in the granite. Round the Comstock Lode also, the diabase is particularly decayed. Moreover, in most mineral-veins there occur layers of clay, earth, or other soft friable loamy substances, to which various mining names are given. The great majority of the remarkable minerals of the southwest of England occur in those parts of the lodes where such soft earths abound. The veins evidently serve as channels for the circulation of water both upward and downward, and to this circulation the decay of some bands into mere clay or earth, and the recrystallization of part of their ingredients into rare or interesting minerals, are to be ascribed. It is observable, also, that the upper parts of pyritous mineral-veins, as they approach the surface of the ground, are usually more or less decomposed from the infiltration of meteoric water, siliceous peroxide of iron and limonite being especially predominant. (Gossan of Cornwall, Chapeau de Fer, Eiserner Hut.)

§ ii. Stocks and Stock-works. (Stöcke, Stockwerke.)

Cavernous spaces dissolved out in such rocks as limestone, or caused by rupture or otherwise, may be of indeterminate shape, and may be filled with one or more vein-stones of ores, either in symmetrical zones following the outline of walls, floor, and roof, or in parallel and roughly horizontal bands (Fig. 321). Irregular metalliferous masses of this kind have long been known in Germany by the name of Stocks (Stöcke) when of large size, smaller aggregations being known as *Butzen* (cones) and *Nester* (tufts). The size of these indefinite accumulations of ore varies from mere nests up to masses 800 feet or more in one direction by 200 feet or more

in another. Hæmatite, brown iron-ore, and galena not infrequently occur in this form in limestone, as in the "pockets" of hæmatite and "flat-works" of galena in the Carboniferous Limestone, and more notably in the ore "chambers" of the Eureka and Richmond mines of Nevada, and the Emma, Flagstaff, and other mines in Utah, from which, in recent years, such vast quantities of ore have been obtained. The "gash" or "rake" veins of galena in the north of England occur in vertical joints of limestone which have been widened by solution, and are sometimes completely cut off

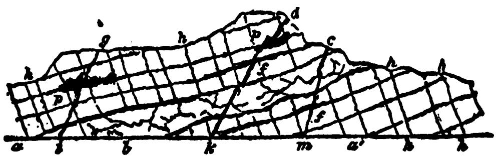

Fig. 321.—Section of Mineral deposits in limestone, Derbyshire (*B.*).

a a', Carboniferous Limestone with intercalated bed of pyroxenic lava or "toadstone" (*b*); *h h h h*, joints traversing the limestone, *i g*, *k d*, *m c*, veins traversing all the rocks and containing vein-stones and ores; *f*, spaces between the beds enlarged by solution and filled with minerals or ores ("flat-works"); *p p*, large irregular cavernous spaces dissolved out of the rock and filled with minerals and ores.

underneath by the floor of shale or sandstone on which the limestone lies. Lenticular aggregations of ore and vein-stone found in granite, as in the southwest of England, where they are known as C a r b o n a s, cannot be due to the infilling of chambers dissolved by subterranean solution. They are usually connected with true fissure-veins; but their mode of origin is not well understood.

Stock-works are portions of the surrounding rock or "country" so charged with veins, nests, and impregnations of ore that they can be worked as metalliferous deposits. The tin stock-works of Cornwall and Saxony are good examples. Sometimes a succession of such stock-works may be observed in the same mine. Among the granites, elvans,

and Devonian slates of Cornwall, tin-ore has segregated in rudely parallel zones or "floors." At Botallack, at the side of ordinary tin lodes, floors of tin-ore from six to twelve feet thick and from ten to forty feet broad occur. The name of *Fahlbands* has been given to portions of "country" which have been impregnated with ores along parallel belts.

Origin of mineral-veins.—Various theories have been proposed to account for the infilling of mineral veins. Of these the most noteworthy are—(1) the theory of lateral segregation—which teaches that the substances in the veins have been derived from the adjacent rocks by a process of leaching, or solution and redeposit; and (2) the theory of infilling from below—according to which the minerals and ores were introduced (*a*) dissolved in water or steam, or (*b*) by sublimation, or (*c*) by igneous fusion and injection.

The structure and characteristic mineral combinations of metalliferous veins are precisely such as would be produced by deposition from aqueous solution. There can hardly be now any doubt that the contents of these veins have generally been deposited by water. But the source from which the metals were derived is not so obvious. The fact that the nature and amount of the minerals, and especially of the ores, in a vein so often vary with the composition of the surrounding rocks shows that these rocks have had an influence on the precipitation of mineral matter in the fissures passing through them, if they were not themselves the source from which the metals were obtained; for, as already remarked, the presence of the heavy metals has now been detected in rocks of almost every kind and age. On the other hand, in some volcanic districts at the present time, various minerals, including silica, both crystalline and chalcedonic, metallic sulphides, and even metallic gold, are being deposited

in fissures up which hot water rises.[8] Each of these modes of origin may in different cases have occurred. It is almost certain, from what we now know of the diffusion of metallic substances, that there must be a decomposition of the rocks on either side of a fissure, perhaps to a great distance, and that a portion of the mineral matter abstracted will be laid down in another form along the fissure-walls. If, on the other hand, the rocks on either side of the fissure are permeated for some distance by hot ascending waters, holding such metalliferous solutions as have been detected in the

Fig. 322.—Unconformability among horizontal strata. Lias resting on Carboniferous Limestone, Glamorganshire (*B.*).

hot springs of California and Nevada, some of the dissolved mineral substances will doubtless be deposited in the fissure, and may even be introduced into the pores and cavities of the adjacent rocks.[9]

Part X. Unconformability

Where one series of rocks, whether of aqueous or igneous origin, has been laid down continuously and without disturbance upon another series, they are said to be *conform-*

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[8] See J. A. Phillips, Q. J. Geol. Soc. xxxv. p. 390.

[9] Henwood, Address. Roy. Inst. Cornwall, 1871. J. A. Phillips, Phil. Mag. November, 1868, December, 1871, July, 1873, March, 1874; "Ore Deposits," 1884, p. 73. J. S. Newberry, School of Mines Quarterly, New York, March, 1880. J. A. Church, "The Comstock Lode," 4to, New York, 1879. Sterry Hunt, "Chemical and Geological Essays," 1875, p. 183. Brough Smyth's "Goldfields of Victoria," Melbourne, 1869. F. Sandberger, "Untersuchungen über Erzgänge," part i.

able. Thus in Fig. 322, the sheets of conglomerate (*b b*) and clays and shales (*c d*), have succeeded each other in regular order, and exhibit a perfect *conformability.* They *overlap* each other, however, each bed extending beyond the edge of that below it, and thereby indicating a gradual subsidence and enlargement of the area of deposit (p. 865). But all these conformable beds repose against an older platform *a a*, with which they have no unbroken continuity. Such a surface of junction is called an *unconformability*, and the upper are said to lie *unconformable* on the lower rocks. The latter may consist of horizontal or inclined clastic strata, or contorted schists, or eruptive massive rocks. In any case, there is a complete break between them and the overlying formation, the beds of which rest successively on different parts of the older mass.

It is evident that this structure may occur in ordinary sedimentary, igneous, or metamorphic rocks, or between any two of these great series. It is most familiarly displayed among clastic formations, and can there be most satisfactorily studied, since the lines of bedding furnish a ready means of detecting differences of inclination and discordance of superposition. But even among igneous protrusions, and in ancient metamorphic masses, distinct evidence of unconformability is occasionally traceable. Wherever one series of rocks is found to rest upon a highly denuded surface of an older series, the junction is unconformable.[1] Hence, an uneven irregularly-worn platform below a succession of mutually conformable rocks is one of the most characteristic features of this kind of structure.

[1] The occurrence of considerable contemporaneous erosion between undoubtedly conformable strata belonging to one continuous geological series has already (pp. 843–847) been described.

It has already been pointed out, that though conformable rocks may usually be presumed to have followed each other continuously without any great disturbance of geographical conditions, we cannot always be safe in such an inference. But an unconformability leaves no room to doubt that it marks a decided break in the continuity of deposit. Hence no kind of geological structure is of higher importance in the interpretation of the history of the stratified formations of a country. In rare cases, an unconformability may occur between two horizontal groups of strata. On the left side of Fig. 322, for instance, the beds *d* follow horizontally upon the horizontal beds (*a*). Were merely a limited section visible, disclosing only this relation of the rocks, the two groups *a* and *d* might be mistaken for conformable portions of one continuous series. Further examination, however, would lead to the detection of evidence that the limestone *a* had been upraised and unequally denuded before the deposition of the overlying strata *b c d*. This denudation would show that the apparent conformability was merely local and accidental, the older rock having really been upraised and worn down before the formation of the newer. In such a case, the upheaval must have been so uniform over some tracts as not to disturb the horizontality of the lower strata, so that the younger deposits lie in apparent conformability upon them.

As a rule, however, it seldom happens that movements of this kind have taken place over an extensive area so equably as not to produce a want of coincidence somewhere between the older and newer rocks. Most frequently, the older formations have been tilted at various angles, or even placed on end. They have likewise been irregularly and often enormously worn down. Hence in-

stead of lying parallel, the younger beds run transgressively across the upturned denuded ends of the older. The greater the disturbance of the older rocks, the more marked is the unconformability. In Fig. 323, the lower series of beds (*c*) has been upturned and denuded before the deposition of the upper series (*a b*) upon it. In this instance, the upper worn surface of the limestones (*c*) has been perforated by boring mollusks below the sandy stratum (*b*).

An unconformability forms one of the great breaks in the geological record. In Fig. 221 (p. 864), by way of illustration, we see at once that a notable hiatus in deposition, and therefore in geological chronology, must exist between the older conformable series, *a b c*, and the later strata by which these are covered. The former had been deposited, folded, upheaved, and worn down before the accumulation of the newer series upon their denuded edges. These changes must have demanded a considerable lapse of time. Yet, looking merely at the structure in itself, we have evidently no means of fixing, even relatively, the length of interval marked by an unconformability. By ascertaining, from some other region, the full suite of formations, we learn what members of the succession are wanting. In this way, it would be discovered that the greater part of the Carboniferous system, the whole of the Permian, and the Trias and the Lias are absent from the ground represented in Fig. 323 (compare Fig. 221). The mere violence of contrast between a set of vertical beds below and a horizontal group above, is in itself no certainly reliable criterion of the relative lapse of time between their deposition; for obviously, an older portion of a given formation might be tilted on end, and be over-

lain unconformably by a later part of the same formation. A set of flat rocks of high geological antiquity may, on the other hand, be conformably covered by a formation of comparatively recent date, yet, in spite of the want of discordance between the two, they might have been separated by a large portion of the total sum of geological time. Further examination will usually suffice to show that the conformability in such cases is only partial or accidental, and that localities may be found where the formations are distinctly unconformable. From the centre of the section in Fig. 324, for example, the two groups of rocks might, on casual examination, be pronounced to be conformable. Yet at short distances on either side, proofs of violent unconformability are conspicuous. It sometimes happens that more than one unconformability may be detected in the same section. Thus in Fig. 325, the break between the quartzite (*q*) and Old Red Sandstone (*s*) is to the eye much more violent and complete than that between the sandstone and the overlying gravels and clays (*d*). Yet the interval separating the epoch of the quartzite from that of the sandstone may have been brief, when compared with the vast lapse of time that intervened between the nearly flat sandstones and overlying superficial deposits. It is by the evidence of organic remains that the relative importance of unconformabilities must be measured, as will be explained in Book V.

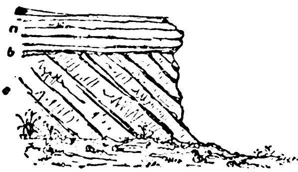

Fig. 323.—Unconformability between horizontal and inclined strata. Inferior Oolite (*a b*) resting on Carboniferous Limestone (*c*); Frome, Somerset (*B.*).

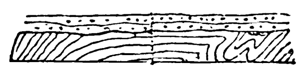
Fig. 324.—Section of local deceptive Conformability.

Paramount though the effect of an unconformability may

be in the geological structure of a country, it must nevertheless, when viewed on the large scale, be merely local. The disturbance by which it was produced will usually be found to have affected a comparatively circumscribed re-

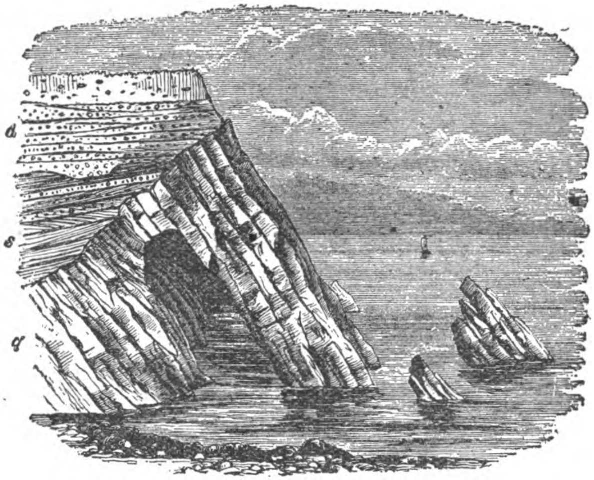

Fig. 325.—Double Unconformability at Cullen, Banffshire.
q, Quartzite; *s*, Old Red Sandstone; *d*, Post-Tertiary Gravels.

gion, beyond the limits of which the continuity of sedimentation may have been undisturbed. We may, therefore, generally expect to be able to fill up the gaps in one district or country from the more complete geological formations of another.

BOOK V

PALÆONTOLOGICAL GEOLOGY

PALÆONTOLOGY treats of the structure, affinities, classification, and distribution in time of the forms of plant and animal life imbedded in the rocks of the earth's crust. Considered from the biological side, it is a part of zoology and botany. A proper knowledge of extinct organisms can only be attained by the study of living forms, while our acquaintance with the history and structure of modern organisms is amplified by the investigation of their extinct progenitors. Viewed, on the other hand, from the physical side, palæontology is a branch of geology. It is mainly in this latter aspect that it will here be discussed.

Palæontology or Palæontological Geology deals with fossils or organic remains preserved in natural deposits, and endeavors to gather from them information as to the history of the globe and its inhabitants. The term fossil, meaning literally anything "dug up," was formerly applied indiscriminately to any mineral substance taken out of the earth's crust, whether organized or not. Ordinary minerals and rocks were thus included as fossils. For many years, however, the meaning of the word has been so restricted as to include only the remains or traces of plants and animals preserved in any natural formation, whether hard rock or loose superficial deposit. The idea of antiquity or relative date is not necessarily involved in this conception of the

term. Thus, the bones of a sheep buried under gravel and silt by a modern flood, and the obscure crystalline traces of a coral in ancient masses of limestone, are equally fossils.[1] Nor has the term fossil any limitation as to organic grade. It includes not merely the remains of organisms, but also whatever was directly connected with or produced by these organisms. Thus, the resin which exuded from trees of long-perished forests is as much a fossil as any portion of the stem, leaves, flowers, or fruit, and in some respects is even more valuable to the geologist than more determinable remains of its parent trees, because it has often preserved in admirable perfection the insects which flitted about in the woodlands. The burrows or trails of a worm, in sandstone or shale, claim recognition as fossils, and indeed are commonly the only indications to be met with of the existence of annelid life among old geological formations. The droppings (coprolites) of fishes and reptiles are excellent fossils, and tell their tale as to the presence and food of vertebrate life in ancient waters. The little agglutinated cases of the caddis-worm remain as fossils in formations from which perchance most other traces of life may have passed away. Nay, the very handiwork of man, when preserved in any natural manner, is entitled to rank among fossils; as where his flint-implements have been dropped into the prehistoric gravels of river-valleys, or where his canoes have been buried in the silt of lake-bottoms.

The term fossil, moreover, suffers no restriction as to the condition or state of preservation of any organism. In some rare instances, the very flesh, skin, and hair of

[1] The word "fossil" is sometimes wrongly used as synonymous with "petrified," and we accordingly find the intolerable barbarism of "sub-fossil."

a mammal have been preserved for thousands of years, as in the case of mammoth carcasses entombed in the frozen mud-cliffs of Siberia.[2] Generally, all or most of the original animal matter has disappeared, and the organism has been more or less completely mineralized or petrified. It often happens that the whole organism has decayed, and a mere cast in amorphous mineral matter, as sand, clay, ironstone, silica, or limestone, remains; yet all these variations must be comprised in the comprehensive term fossil.

Two preliminary questions demand attention: in the first place, how remains of plants and animals come to be entombed in rocks, and in the second, how they have been preserved there so as to be now recognizable.

§ i. Conditions for the entombment of organic remains.—If what takes place at the present day may fairly be taken as an indication of what has been the ordinary condition of things in the geological past, there must have been so many chances against the conservation of either animal or plant remains, that their occurrence among stratified formations should be regarded as exceptional, and as the result of various fortunate accidents.

1. On Land.—Let us consider, in the first place, what chances exist for the preservation of remains of the present fauna and flora of a country. The surface of the land may be densely clothed with forest, and abundantly peopled with animal life. But the trees die and moulder into soil. The animals, too, disappear, generation after generation, and leave few perceptible traces of their existence. If we were not aware from authentic records that central and

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[2] For particulars of a recent exhumation see "Beiträge zur Kenntniss des Russischen Reiches," Bd. III., 1887, p. 175.

northern Europe was covered with vast forests at the beginning of our era, how could we know this fact? What has become of the herds of wild oxen, the bears, wolves, and other denizens of the lowlands of primeval Europe? For unknown ages, too, the North American prairies have been roamed over by countless herds of buffaloes, yet, except here and there a skull and bones of some comparatively recent individual, every trace of these animals has disappeared from the surface.[8] How could we prove from the examination of the soil either in Europe or North America that such creatures, though now locally extinct, had once abounded there? We might search in vain for any superficial relics of them, and should learn by so doing that the law of nature is everywhere "dust to dust."

The conditions for the preservation of evidence of terrestrial (including freshwater) plant and animal life, must, therefore, be always local, and, so to say, exceptional. They are supplied only where organic remains can be protected from air and superficial decay. Hence, they may be observed in lakes, peat-mosses, deltas at river-mouths, caverns, deposits of mineral-springs and volcanoes.

a. Lakes.—Over the floor of a lake, deposits of silt, peat, marl, etc., are formed. Into these, the trunks, branches, leaves, flowers, fruits, or seeds of plants from the neighboring land may be carried, together with the bodies of vertebrates, birds, and insects. An occasional storm may blow the lighter débris of the woodlands into the water. Such portions of the wreck as are not washed ashore again, may sink to the bottom, where they will, for the most part, probably rot away, so that, in the end, only a very small fraction of the whole vegetable matter, cast over the lake by the wind, is covered up and preserved at the bottom. In like manner, the remains of winged and four-footed animals, swept by

[8] See Jules Marcou, "Lettres sur les roches du Jura," p. 103.

winds or by river-floods into the lake, run so many risks of dissolution, that only a proportion of them, and probably merely a small proportion, is preserved. When we consider these chances against the conservation of the vegetable and animal life of the land, we must admit that, at the best, lake-bottoms can contain but a meagre and imperfect representation of the abundant life of the adjacent hills and plains. Lakes, however, have a distinct flora and fauna of their own. Their aquatic plants may be entombed in the gathering deposits of the bottom. Their mollusks, of characteristic types, sometimes form, by the accumulation of their remains, sheets of soft calcareous marl (pp. 244, 812), in which many of the undecayed shells are preserved. Their lacustrine fishes, likewise, must no doubt often be entombed in the silt or marl.

b. Peat-mosses.—Wild animals, venturing on the more treacherous watery parts of peat-bogs, are sometimes engulfed or "laired." The antiseptic qualities of the peat preserve their remains from decay. Hence, from European peat-mosses, numerous remains of deer and oxen have been exhumed. Evidently the larger beasts of the forest ought chiefly to be looked for in these localities (p. 802).

c. Deltas at river-mouths.—It is obvious that, to some extent, both the flora and the fauna of the land may be buried among the sand and silt of deltas (p. 677). But though occasional or frequent river-floods sweep down trees, herbage, and the bodies of land-animals, the carcasses so transported run every risk of having their bones separated and dispersed,[4] or of decaying or being otherwise destroyed, while still afloat; and even if they reach the bottom, they tend to dissolution there, unless speedily covered up and protected by fresh sediment. Delta-formations can therefore scarcely be expected to preserve more than a meagre outline of a varied terrestrial flora and fauna.

d. Caverns.—These are eminently adapted for the preservation of the higher forms of terrestrial life (pp. 625, 827). Most of our knowledge of the prehistoric mammalian fauna of Europe is derived from what has been disinterred from *bone-caves.* As these recesses lie, for the most part, in limestone or in calcareous rock, their floors are commonly coated with stalagmite from the drip of the roof; and as this deposit

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[4] Lower jaws, for instance, because they are among the earliest parts of the skeleton of a floating carcass to drop off, are not infrequently met with as fossils.

is of great closeness and durability, it has effectually preserved whatever it has covered or enveloped. The caves have, in many instances, served as dens for predatory beasts, like the hyena, cave-lion, and cave-bear, which sometimes dragged their prey into these recesses. In other cases, they have been merely holes whither different animals crawled to die, or into which they fell or were swept by inundations. Under whatever circumstances the animals left their remains in these subterranean retreats, the bones have been covered up and preserved. Still we must admit that, after all, only a small fraction of the animals of the time would enter the caves, and therefore that the evidence of the cavern-deposits, profoundly interesting and valuable as it is, presents us with merely a glimpse of one aspect of the life of the land.

e. Deposits of mineral-springs.—The deposits of mineral matter, resulting from the evaporation of mineral springs on the surface of the ground, serve as receptacles for occasional leaves, land-shells, insects, dead birds, small mammals, and other remains of the plant and animal life of the land (pp. 622, 808).

f. Volcanic deposits.—Sheets of lava and showers of volcanic dust may entomb terrestrial organisms (pp. 343, 985). It is obvious, however, that even over the areas wherein volcanoes occur and continue active, they can only to a very limited extent entomb and preserve the flora and fauna of the land.

2. In the Sea.—In the next place, if we turn to the sea, we find certainly more favorable conditions for the preservation of organic forms, but also many circumstances which operate against it.

a. Littoral deposits.—While the level of the land remains stationary, there can be but little effective entombment of marine organisms in littoral deposits; for only a limited accumulation of sediment will be formed until subsidence of the sea-floor takes place. In the trifling beds of sand or gravel thrown up by storms above the limits of ordinary wave-action on a stationary shore, only the harder and more durable forms of life, such as the stronger gasteropods and lamellibranchs, which can withstand the triturating effects of the beach-waves, are likely to remain uneffaced (p. 762).

b. Deeper-water terrigenous deposits.—Below tide-marks,

along the margin of land whence sediment is derived, conditions are more favorable for the preservation of marine organisms. Sheets of sand and mud are there laid down, wherein the harder parts of many forms of life may be entombed and protected from decay (p. 763). But probably only a small proportion of the fauna that crowds these marginal waters of the ocean, with perhaps an occasional pelagic species, may be expected to occur in such deposits. Moreover, for the entombment and preservation of the remains of these organisms, there must obviously be a sufficiently abundant and rapid deposit of sediment, combined with a slow depression of the sea-bottom. Under the most favorable conditions, therefore, the organic remains actually preserved will usually represent little more than a mere fraction of the whole assemblage of life in these juxta-terrestrial parts of the ocean.

c. *Abysmal deposits.*—In proportion to distance from land, the rate of deposition of sediment on the sea-floor must become feebler, until in the remote central abysses it reaches a hardly appreciable minimum, while at the same time the solution of calcareous organisms may become marked in deep water (p. 767). Except, therefore, where organic deposits such as ooze are forming in these more pelagic regions, the conditions must be on the whole unfavorable for the preservation of any adequate representation of the deep-sea fauna. Hard enduring objects, such as teeth and bones, may slowly accumulate and be protected by a coating of peroxide of manganese, or of silicates, such as are now forming here and there over the deep sea-bottom. Yet a deposit of this nature, if raised into land, would supply but a meagre picture of the life of the sea.

In considering the various conditions under which marine organisms may be entombed and preserved, we must take into account certain occasional phenomena, when sudden, or at least rapid and extensive, destruction of the fauna of the sea may be caused. (1) Earthquake shocks have been followed by the washing ashore of vast quantities of dead fish.[5] (2) Violent storms, by driving shoals of fishes into shallow water and against rocks, produce enormous destruction. Dr. Leith Adams describes the coast of part of the Bay of Fundy as being covered to a depth of a foot in some places with dead fish, dashed ashore by a storm on the 24th of Septem-

[5] C. Forbes, Q. J. Geol. Soc. xiv. 1858, p. 294.

ber, 1867.[6] (3) Copious discharges of fresh water into the sea have been observed to cause extensive mortality among marine organisms. Thus, during the S.W. monsoon and accompanying heavy rains, the west coasts of some parts of India are covered with dead fish thrown ashore from the sea.[7] (4) A sudden irruption of the outer sea into a sheltered and partially brackish inlet may cause the extinction of many of the denizens of the latter, though a few may be able to survive the altered conditions.[8] (5) Volcanic explosions have been observed to cause considerable destruction to marine life, either from the heat of the lava or from the abundance of ashes or of poisonous gases. (6) Want of oxygen, when fishes are crowded together in frightened shoals, or when, burrowing in sand and mud, they are overwhelmed with rapidly accumulating detritus, is another cause of mortality.[9] (7) Shoals of fish are sometimes driven ashore by the large predatory denizens of the deep, such as whales and porpoises. (8) Too much or too little heat in shallow water leads to the destruction of fish. Large numbers of salmon are sometimes killed in the pools of a river during dry and hot weather. (9) Considerable mortality occasionally arises along the littoral zone from the effects of severe frost. (10) Various diseases and parasites affect fish, and lead directly to their death, or weaken them so that they are more easily caught by their enemies.[10] Such phenomena suggest probable causes of death in the case of fossil fishes, whose remains are sometimes crowded together in various geological formations, as, for example, in the Old Red Sandstone.

Of the whole sea-floor, the area best adapted for preserving organic exuviæ is obviously that belt in which life is most varied and abundant, and where, along the margin of the land, fresh layers of sediment, transported by rivers and currents from the adjacent shores, are laid down. The most

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[6] Q. J. Geol. Soc. xxix. p. 303.

[7] Denison, op. cit. xviii. p. 453, Nature (December 19, 1872, p. 124) gives another instance.

[8] Forchhammer, Edin. New. Phil. Journ. xxxi. p. 69. Nature, i. p. 454; xiii. p. 107.

[9] Sir J. W. Dawson, Geologist, ii. 1859, p. 1216.

[10] For fuller references, see an interesting paper by Prof. T. Rupert Jones, Geol. Mag. 1882, p. 533.

favorable conditions for the accumulation of a thick mass of marine fossiliferous strata will arise when the area of deposit is undergoing a gradual subsidence. If the rate of depression and that of deposit be equal, or nearly so, the movement may conceivably continue for a vast period without producing any great apparent change in marine geography, and even without seriously affecting the distribution of life over the sea-floor within the area of subsidence. Hundreds or thousands of feet of sedimentary strata may conceivably be in this way heaped up round the continents, containing a fragmentary series of remains, chiefly forms of shallow-water life which had hard parts capable of preservation.

There can be little doubt that such has, in fact, been the history of the main mass of stratified formations in the earth's crust. These piles of marine strata have unquestionably been laid down for the most part in comparatively shallow water, within the area of deposit of terrestrial sediment. Their great depth seems only explicable by prolonged and repeated movements of subsidence, sometimes interrupted, however, as we know, by other movements of a contrary kind. These geographical changes affected at once the deposition of inorganic materials and the succession of organic forms. One series of strata is sometimes abruptly succeeded by another of a very different character, and we not uncommonly find a corresponding contrast between their respective organic contents.

It follows, from these conditions of sedimentation, that representatives of the abysmal deposits of the central oceans are not likely to be met with among the geological formations of past times. Thanks to the great work done by the "Challenger" Expedition, we know what are the leading characters of the accumulations now forming on the deeper

parts of the ocean-floor. So far as we yet know, they have no analogues among the formations of the earth's crust. They differ, indeed, so entirely from any formation which geologists have considered to be of deep-water origin as to indicate that, from early geological times, the present great areas of land and sea have remained on the whole where they are, and that the land consists mainly of strata formed of terrestrial débris laid down at successive epochs in the surrounding comparatively shallow seas.

§ ii. **Preservation of organic remains in mineral masses.**— The condition of the remains of plants and animals in rock-formations depends, first, upon the original structure and composition of the organisms, and, secondly, upon the manner in which their "fossilization," that is, their entombment and preservation, has been effected.

1. Influence of original structure and composition.—The durability of organisms is determined by their composition and structure.

The internal skeletons of most vertebrate animals consist mainly of phosphate of lime; in saurians and fishes, there is also an exo-skeleton of hard bony plates or of scales. It is these durable portions that remain as evidence of the former existence of vertebrate life. The hard parts of invertebrates present a greater variety of composition. In the vast majority of cases, they consist of calcareous matter, either calcite or aragonite. The carbonate of lime is occasionally strengthened by phosphate, while in a few cases, as in the horny brachiopods, in *Conularia*, *Serpula*, and some other forms, the phosphate is the chief constituent.[11] Next in abundance to lime is silica, which constitutes the frustules of diatoms and the harder parts of many protozoa, and is found also in the teeth of some mollusks. The integuments of insects, the carapaces of crustacea, and some

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[11] Logan and Hunt, Amer. Journ. Sci. xvii. 1854, p. 235.

other organisms, are composed fundamentally of chitin,[12] a transparent horny substance which can long resist decomposition. In the vegetable kingdom, the substance known as cellulose forms the essential part of the framework of plants. In dry air, it possesses considerable durability, also when thoroughly waterlogged and excluded from meteoric influences. In the latter condition, imbedded amid mud or sand, it may last until gradually petrified.[13]

It is a familiar fact that in the same stratum different organisms occur in remarkably different states of conservation. This is sometimes strikingly exemplified among the mollusca. The conditions for their preservation may have been the same, yet some kinds of shells are found only as empty molds or casts, while others still retain their form, composition, and structure. This discrepancy, no doubt, points to original differences of composition or structure. The aragonite shells of a stratum may be entirely dissolved, while those of calcite may remain.[14] The presence, therefore, of calcite forms only does not necessarily imply that others of aragonite were not originally present. But the conditions of petrifaction have likewise greatly varied. In the clays of the Mesozoic formations, for example, cephalopods may be exhumed retaining even their pearly nacre, while in corresponding deposits among the Palæozoic systems they are merely crystalline calcite casts.

2. Fossilization.—The condition in which organic remains have been entombed and mineralized may be reduced to three leading types.

(1) *The original substance is partly or wholly preserved.*—Several grades may be noticed: (*a*) where the entire animal substance is retained, as in the frozen carcasses of mammoths in the Siberian cliffs; (*b*) where the organism has been mummified by being incased in resin or gum (insects in amber); (*c*) where the organism has been carbonized with or without retention of its structure, as is characteristically shown in peat, lignite, and coal; (*d*) where a variable por-

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[12] According to C. Schmidt, the composition of this substance is C, 46·64; H, 6·60; N, 6·66; O, 40·20. The brown chitin of Scottish Carboniferous scorpions is hardly distinguishable from that of recent species.

[13] On cellulose and coal, see C. F. Cross and E. J. Bevan, Brit. Assoc. 1881, Sects. p. 603.

[14] See ante, pp. 216, 243, and authorities there cited.

tion of the original substance, and especially the organic matter, has been removed, as happens with shells and bones: this is no doubt one of the first steps toward petrifaction.

(2) *The original substance is entirely removed, with retention merely of external form.*—Mineral matter gathers round the organism and hardens there, while the organism itself decays. Eventually a mere mold of the plant or animal is left in stone. Every stage in this process may be studied along the margin of calcareous springs and streams (ante, p. 808). The lime in solution is precipitated round fibres of moss, leaves, twigs, etc., which are thereby incrusted with mineral matter. While the crust thickens, the organism inside decays, until a mere hollow mold of its form remains. Among stratified rocks, molds of organic forms are of frequent occurrence. They may be filled up with mineral matter, washed in mechanically or deposited as a chemical precipitate, so that a cast in stone replaces the original organism. Such casts are particularly common in sandstone, which, being a porous rock, has allowed water to filter through it and remove the substance of inclosed plant-stems, shells, etc. In the sandstones of the Carboniferous system, casts in compacted sand of stems of *Lepidodendron* and other plants are abundant. It is obvious that in casts of this kind no trace remains of the original structure of the organism, but merely of its external form.

(3) *The original substance is molecularly replaced by mineral matter with partial or entire preservation of the internal structure of the organism.*—This is the only true petrifaction. The process consists in the abstraction of the organic substances, molecule by molecule, and in their replacement by precipitated mineral matter. So gradual and thorough has this interchange often been, that the minutest structures of plant and animal have been perfectly preserved. Silicified wood is a familiar example (see p. 619).

The chief substance which has replaced organic forms in rocks is calcite, either crystalline or in an amorphous granular condition. In assuming a crystalline (or fibrous) form, this mineral has often observed a symmetrical grouping of its component individuals, these being usually placed with their long axes perpendicular to the surface of an organism. In many cases, among invertebrate remains, the calcite now visible is pseudomorphous after aragonite (p. 216). Next in abundance as a petrifying medium is silica, most commonly in the chalcedonic form, but also as quartz. It is specially frequent in some limestones, as chert and

flint, replacing the carbonate of lime in mollusks, echinoderms, corals, etc. It also occurs in irregular aggregates, in which organisms are sometimes beautifully preserved. It forms a frequent material for the petrifaction of fossil wood. Silicification, or the replacement of organisms by silica, is the process by which minute organic structures have been most perfectly preserved. In a microscopic section of silicified wood, the organization of the original plant may be as distinct as in the section of any modern tree. Pyrites and marcasite, especially the latter, are common replacing minerals, abundant in argillaceous deposits, as, for example, among the Jurassic and Cretaceous clays. Siderite has played a similar part among the ironstones of the Coal-measures, where shells and plants have been replaced by it. Many other minerals are occasionally found to have been substituted for the original substance of organic remains. Among these may be mentioned glauconite (replacing or filling foraminifera), vivianite (specially frequent as a coating on the weathered surface of scales and bones), barytes, celestine, gypsum, talc, lead-sulphate, carbonate, and sulphide; copper-sulphide and native copper; hæmatite and limonite; zinc-carbonate and sulphide; cinnabar; silver chloride and native silver; sulphur, fluorite, phosphorite.[15]

§ iii. **Relative Palaeontological value of organic remains.** —As the conditions for the preservation of organic remains exist more favorably under the sea than on land, relics of marine must be far more abundantly conserved than those of terrestrial organisms. This is true to-day, and has doubtless been true in all past geological time. Hence, for the purposes of the geologist, fossil remains of marine forms of life far surpass all others in value. Among them, there will necessarily be gradations in importance, regulated chiefly by their possession of hard parts, readily susceptible of preservation among marine deposits. Among the Protozoa, foraminifers, radiolarians, and sponges, pos-

[15] Roth, "Chem. Geol." i. p. 605. Jannettaz, Bull. Soc. Geol. France (3), vii. p. 102.

sessing siliceous or calcareous organizations, have been preserved in deposits of all ages. Of the Cœlenterates, those which, like the corals, secrete a calcareous skeleton are important rock-builders. The Echinoderms have been so abundantly preserved that their geological history and development are better known than those of most other classes of invertebrates. The Annelids, on the other hand (except where they have been tubicolar), have almost entirely disappeared, though their former presence is often revealed by the trails they have left upon surfaces of sand and mud. Of all the marine tribes which live within the juxta-terrestrial belt of sedimentation, unquestionably the Mollusca stand in the front rank, as regards their aptitude for becoming fossils. In the first place, they almost all possess a hard durable shell, composed chiefly of mineral matter, capable of resisting considerable abrasion, and readily passing into a mineralized condition. In the next place, they are extremely abundant both as to individuals and genera. They occur on the shore up to high-water mark, and range thence down into the abysses. Moreover, they appear to have possessed these qualifications from early geological times. In the marine Mollusca, therefore, we have a common ground of comparison between the stratified formations of different periods. They have been styled the alphabet of palæontological inquiry. It will be seen, as we proceed, how much, in the interpretation of geological history, depends upon the testimony of sea-shells.

Turning next to the organisms of the land, we perceive that the abundant terrestrial flora has a comparatively small chance of being well represented in a fossil state; that indeed, as a rule, only that portion of it of which the leaves, twigs, flowers, fruits or trunks are blown into lakes, or swept

down by rivers, is likely to be partially preserved. Terrestrial plants, therefore, occur in comparative rarity among stratified rocks, and furnish in consequence only limited means of comparison between the formations of different ages and countries (see pp. 1097, 1111). Of land animals, the vast majority perish, and leave no permanent trace of their existence. Predatory and other forms, whose remains may be looked for in caverns or peat-mosses, must occur more numerously in the fossil state than birds, and are correspondingly more valuable to the geologist for the comparison of different strata.

Another character determines the relative importance of fossils as geological monuments. All organisms have not the same inherent capability of persistence. The longevity of an organic type has, on the whole, been in inverse proportion to its perfection. The more complex its structure, the more susceptible has it been of change, and consequently the less likely to be able to withstand the influences of changing climate, and other physical conditions. A living species of foraminifer or brachiopod, endowed with comparative indifference to its environment, may spread over a vast area of the sea-floor, and the same want of sensibility enables it to endure through the changing physical conditions of successive geological periods. It may thus possess a great range, both in space and time. But a highly-specialized mammal is usually confined to but a limited extent of country, and to a narrow chronological range.[16]

[16] The great value of mammalian remains for purposes of geological chronology has been well enforced by Prof. Marsh. See especially his address to the American Association for the Advancement of Science, 30th August, 1877, and a subsequent paper in Amer. Journ. Sci. xlii. 1891, p. 336. Mr. W. T. Blanford points out that, in some cases at least, fluviatile mollusks have been more short-lived than terrestrial mammals. Address, Geol. Section, Brit. Assoc. 1884.

§ iv. Uses of Fossils in Geology.—Apart from their profound interest as records of the progress of organized being upon the earth, fossils serve two main purposes in geological research: (1) to throw light upon former conditions of physical geography, such as the presence of land, rivers, lakes, and seas, in places where they do not now exist, upon changes of climate, and upon the former distribution of plants and animals; and (2) to furnish a guide in geological chronology whereby rocks may be classified according to relative date, and the facts of geological history may be arranged and interpreted as a connected record of the earth's progress.

1. Changes in Physical Geography.—A few examples will suffice to show the manifold assistance which fossils furnish to the geologist in the elucidation of ancient geography.

(*a*) Former land-surfaces are revealed by the presence of tree-stumps in their positions of growth, with their roots branching freely in the underlying stratum, which, representing the ancient soil, often contains leaves, fruits, and other sylvan remains, together with traces of the bones of land animals, remains of insects, land-shells, etc. Ancient woodland surfaces of this kind, found between tide-marks, and even below low-water line, round different parts of the British coast, unequivocally prove a subsidence of the land ("Submerged Forests," p. 489). Of more ancient date are the "dirt-beds" of Portland (Book VI. Part III. Section ii. § 2), which, by their layers of soil and tree-stumps, show that woodlands of cycads sprang up over an upraised sea-bottom and were buried beneath the silt of a river or lake. Still further back in geological history come the coal-growths of the Carboniferous period, which, with their "under-clays" or soils, point to wide jungles of terrestrial or aquatic plants, like the modern mangrove-swamps that were successively submerged and covered with sand or silt (Book VI. Part II. Sect. iv. § 1).

(*b*) The former existence of lakes can be satisfactorily

proved from beds of marl or lacustrine limestone full of freshwater shells, or from fine silt with leaves, fruits, and insect remains. Such deposits are growing abundantly at the present day, and they occur at various horizons among the geological formations of past times. The well-known Nagelflue of Switzerland—a mass of conglomerate attaining a thickness of more than 1000 feet—can be shown from its fossil contents to be essentially a lacustrine deposit (Book VI. Part IV. Sect. ii. § 2). Still more important are the ancient Eocene and Miocene lake-formations of North America, whence so rich a terrestrial and lacustrine flora and fauna have been obtained (Book VI. Part IV. Sect. i. § 1).

(*c*) Old sea-bottoms are vividly brought before us by beds of marine shells and other organisms. Layers of water-worn gravel and sand, with rolled shells of littoral and infra-littoral species, unmistakably mark the position of a former shore-line. Deeper water is indicated by finer muddy sediment, with relics of the fauna that prevails beneath the reach of waves and ground-swell. Limestones full of corals, or made up of crinoids, point to the slow, continuous growth and decay of generation after generation of organisms in clear sea-water.

(*d*) Variations in the nature of the water, or of the sea-bottom, may sometimes be shown by changes in the size or shape of the organic remains. If, for example, the fossils in the central and lower parts of a limestone are large and well-formed, but in the upper layers become dwarfed and distorted, we may reasonably infer that the conditions for their continued existence at the locality must have been gradually impaired. The final complete cessation of these favorable conditions is shown by the replacement of limestone by shale, indicative of the water having become muddy, and by the disappearance of the organisms, which had shown their sensitiveness to the change.

(*e*) The proximity of land at the time when a fossiliferous stratum was in the course of accumulation may be sufficiently proved by mere lithological characters, as has been already explained; but the conclusion may be further strengthened by the occurrence of leaves, stems, and other fragments of terrestrial vegetation, with remains of insects, birds, or terrestrial mammals, which, if found in some numbers in certain strata intercalated among others containing marine organisms, would make it improbable that they had been drifted far from land (see p. 765).

(*f*) The existence of different conditions of **climate** in former geological periods is satisfactorily demonstrated from the testimony of fossils. Thus, an assemblage of the remains of palms, gourds, and melons, with bones of crocodiles, turtles, and sea-snakes, proves a sub-tropical climate to have prevailed over the south of England in the older Tertiary ages (Book VI. Part IV. Sect. i. § 1). On the other hand, the extension of a cold or arctic climate far south into Europe during post-Tertiary time can be shown from the existence of remains of arctic animals, even in the south of England and of France (Book VI. Part V.). This is a use of fossils, however, where great caution must be observed. We cannot affirm that, because a certain species of a genus lives now in a warm part of the globe, every species of that genus must always have lived in similar circumstances. The well-known examples of the mammoth and woolly rhinoceros that lived in the cold north, while their modern representatives inhabit some of the warmest regions of the globe, may be usefully remembered as a warning against any such conclusion. When, however, not one fossil merely, but the whole assemblage of fossils in a group of rocks, finds its modern analogy in a certain general condition of climate, we may, at least tentatively, infer that the same kind of climate prevailed where that assemblage lived. Such an inference would become more and more unsafe in proportion to the antiquity of the fossils, and their divergence from existing forms.[17]

As an illustration of this application of the evidence of fossils in the interpretation of ancient conditions of geography at different geological periods, reference may be made more especially to the investigation of the various basins in which the Jurassic rocks of Europe were deposited. The positions of the seas and lands, and the variations of climate have been ascertained with sufficient definiteness to give us

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[17] See Neumayr, Nature, xlii. 1890, pp. 148, 175. This author specially devoted himself to the study of ancient climates as indicated by fossils. As an illustration of his methods consult his essay on the climatic zones of Jurassic and Cretaceous time, Denksch. Akad. Wien, xlvii. 1883; also the same work, vol. l. 1885. "Fossil plants as tests of Climate"—the Sedgwick Prize Essay for 1892. By A. C. Seward. Cambridge, C. J. Clay, 1892.

some conception of the physical geography of that part of the globe during early Mesozoic time.[18]

2. Geological Chronology.—Although absolute dates cannot be fixed in geological chronology, it is not difficult to determine the relative age of different strata. For this purpose the fundamental law is based on the "order of superposition" (pp. 873, 1121): in a series of stratified formations, the older underlie the younger. It is not needful that we should actually see the one lying below the other. If a continuous conformable succession of strata dips steadily in one direction, we know that the beds at the one end must underlie those at the other, because we can trace the whole succession of beds between them. Rare instances occur, where strata have been so folded by great terrestrial disturbance that the younger are made to underlie the older. But this inversion can usually be made clear from other evidence. The true order of superposition is decisive of the relative ages of stratified rocks.

The order of sequence having been determined, it is needful to find some means of identifying a particular formation elsewhere, when its stratigraphical relations may possibly not be visible. At first, it might be thought that the mere external aspect and mineral characters of the rocks ought to be sufficient for this purpose. Undoubtedly these features may suffice within the same limited region in which the order of sequence has already been determined. But as we recede from that region they become more and more unreliable. That this must be the case will readily appear, if we reflect upon the conditions under which sedimentary

[18] See especially Neumayr, Verh. Geol. Reichsanst. 1871, p. 54, Jahrb. Geol. Reichsanst. xxviii. 1878, and his essay cited in the foregoing note.

accumulations have been formed. The markedly lenticular nature of these deposits has already been described (p. 860). At the present day, the sea-bottom presents here a bank of gravel, there a sheet of sand, elsewhere layers of mud, or of shells, or of organic ooze, all of which are in course of deposit simultaneously, and will as a rule be found to shade off laterally into each other. The same diversity of contemporaneous deposits has obtained from the earliest geological periods. Conglomerates, sandstones, shales, and limestones occur on all geological horizons, and replace each other even on the same platform. The Coal-measures of Pennsylvania are represented west of the Rocky Mountains by thousands of feet of massive marine limestones. The white Chalk of England lies on the same geological horizon with marls and clays in North Germany, with thick sandstones in Saxony, with hard limestone in the south of France. Mere mineral characters are thus quite unreliable, save within comparatively restricted areas.

The solution of this problem was found, and was worked out for the Secondary rocks of England, by William Smith at the end of last century. It is supplied by organic remains, and depends upon the law that the order of succession of plants and animals has been similar all over the world. According to the order of superposition, the fossils found in any deposit must be older than those in the deposit above, and younger than those in that below. This order, however, must be first accurately determined by a study of the actual stratigraphy of the formations; for, so far as regards organic structure or affinities, there may be no discoverable reason why a particular species should precede or follow another. Unless, for example, we knew from observation that *Rhynchonella pleurodon* is a shell of the Carboniferous

Limestone, and *Rhynchonella tetrahedra* is a shell of the Lias, we could not, from mere inspection of the fossils themselves, pronounce as to their real geological position."[19] It is quite true that, by practice, a palæontologist has his eye so trained that he can make shrewd approximations to the actual horizon of fossils which he may never have seen before (and this is more especially true in regard to the mammalia, as will be immediately adverted to), but he can only do this by availing himself of a wide experience, based upon the ascertained order of appearance of fossils, as determined by the law of superposition. For geological purposes, therefore, and, indeed, for all purposes of comparison between the faunas and floras of different periods, it is absolutely essential, first of all to have the order of superposition of strata rigorously determined. Unless this is done, the most fatal mistakes may be made in palæontological chronology. But when it has once been done in one typical district, the order thus established may be held as proved for a wide region where, from paucity of sections, or from geological disturbance, the true succession of formations cannot be satisfactorily determined.

The order of superposition having been determined in a great series of stratified formations, it is found that the fossils at the bottom are not quite the same as those at the top of the series. As we trace the formations upward, we discover that species after species of the lowest platforms disappears, until perhaps not one of them is found. With the

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[19] The derivation of some forms by descent from others may be inferred with more or less probability, and such genetic affinities may furnish valuable suggestions to the palæontologist. But that the risk of erroneous interpretation and fanciful deduction in such matters is real and serious was well shown in the discussion of the presumed derivation of the Olenellidian trilobites from the Paradoxidian forms, until it was shown that the former were really the precursors of the latter.

cessation of these older species, others make their entrance. These, in turn, are found to die out and to be replaced by newer forms. After patient examination of the rocks, it is ascertained that every well-marked formation is characterized by its own species or genera (type-fossils, Leitfossilien) or by a general assemblage or *facies* of organic forms. This can only, of course, be determined by actual practical experience over an area of some size. The characteristic fossils are not always the most numerous; they are those which occur most constantly and have not been observed to extend their range above or below a definite geological horizon or platform. For the determination of geological chronology, as already pointed out, it may be affirmed as a general principle that the higher and more specialized the type of organism the more local is its area in space and the more limited its range in time. Hence mammalian remains have a special value in this respect.[20] But some invertebrate groups possess great importance as fixing stratigraphical horizons; as, for example, the ammonites in the Jurassic and the graptolites in the Silurian system.

As illustrations of type-fossils characteristic of some of the larger subdivisions of the Geological Record, the following may be given. Lepidodendra and Sigillaria are typical of Old Red Sandstone and Carboniferous deposits; Graptolites of the Silurian system; Trilobites of Palæozoic rocks from Cambrian to Carboniferous, Cystideans of the older Palæozoic rock-groups. Orthoceratites are Palæozoic, and Ammonites are Mesozoic; Ichthyosaurs and Plesiosaurs, Mesozoic; Nummulites, Palæotherium, Anoplotherium, Hyopotamus, and Anthracotherium belong to older Tertiary, and Mastodon, Elephas, Hyena, Cervus, and Equus to younger Tertiary and recent time. The occurrence of

[20] Consult the papers of Prof. Marsh quoted on p. 1083, and see especially the plate in the second paper in which the successive mammalian zones in the Geological Record of North America are given.

such organisms in any rock at once indicates the great division of geological time to which the rock should be assigned.

The type-fossils of a system or formation, having been ascertained from a sufficiently prolonged and extended experience, serve to identify that series of rocks in its progress across a country. Thus, as we trace a formation into tracts where it would be impossible to determine the true order of superposition, owing to the want of sections, or to the disturbed condition of the rocks, we can employ the type-fossils as a means of identification, and speak with confidence as to the succession of the rocks. We may even demonstrate that, in some mountainous ground, the strata have been turned completely upside down, if we can show that the fossils in what are now the uppermost layers ought properly to lie underneath those in the beds below them.

Prolonged study of the succession of organic types in the geological past all over the world, has given palæontologists some confidence in fixing the relative age of fossils belonging even to previously unknown species or genera, and occurring under circumstances where no order of superposition has been made out. For instance, the general sequence of mammalian types having now been settled by the law of superposition, the horizon of a mammaliferous deposit may be approximately determined by the grade or degree of evolution denoted by its mammalian fossils. Thus, should remains be generically abundant, differing from those now living and presenting none of the extreme contrasts which are now found among our higher animals, should they embrace neither true ruminants, nor solipeds, nor proboscidians, nor apes, they might with high probability be referred to the Eocene period.[21] Reasoning of this kind must be

[21] Gaudry, "Les Enchainements du Monde Animal," 1878, p. 246.

based, however, upon a wide basis of evidence, seeing that the progress of development has been far from equal in all ranks of the animal world.

Observations made over a large part of the surface of the globe have enabled geologists to divide the stratified part of the earth's crust into systems, formations, and groups (p. 1127). These subdivisions are frequently marked off from each other by lithological characters. But, as already remarked, mere lithological differences afford at the best but a limited and local ground of separation. Two masses of sandstone, for example, having exactly the same general external and internal characters, may belong to very different geological periods. On the other hand, a series of limestones in one locality may be the exact chronological equivalent of a set of sandstones and conglomerates at another, and of a series of shales and clays at a third.

Some clew is accordingly needed which will permit the divisions of the stratified rocks to be grouped and compared chronologically. This fortunately is well supplied by their characteristic fossils. Each formation being distinguished by its own assemblage of organic remains, it can be followed and recognized even amid the crumplings and dislocations of a disturbed region. The same general succession of organic types has been observed over a large part of the world, though, of course, with important modifications in different countries. The similarity of succession has been called *homotaxis*—a term which expresses the fact that the order in which the leading types of organized existence have appeared upon the earth has been similar even in widely separated regions.[22]

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[22] Huxley, Q. J. Geol. Soc. xviii. 1862, p. xlvi.

It is evident that, in this way, a method of comparison is furnished whereby the stratified groups of different parts of the earth's crust can be brought into relation with each other. We find, for example, that a certain group of strata is characterized in Britain by certain genera and species of corals, brachiopods, lamellibranchs, gasteropods, and cephalopods. A group of rocks in Bohemia, differing more or less from the British type in lithological aspect, contains on the whole the same genera, and some even of the same species. In Scandinavia, a set of beds may be seen, unlike perhaps in external characters to the British type, but yielding many of the same fossils. In Canada and parts of the northern United States, other rocks inclose some of the same, and of closely allied genera and species. All these groups of strata, having the same general facies of organic remains, are classed together as *homotaxial*, that is, as having been deposited during the same relative period in the general progress of life in each region.

It was at one time believed, and the belief is still far from extinct, that groups of strata, characterized by this community or resemblance of organic remains, were chronologically contemporaneous. But such an inference rests upon most insecure grounds. We may not be able to disprove the assertion that the strata were strictly coeval, but we have only to reflect on the present conditions of zoological and botanical distribution, and of modern sedimentation, to be assured that the assertion of contemporaneity is a mere assumption. Consider, for a moment, what would happen were the present surface of any portion of central or southern Europe to be submerged beneath the sea, covered with marine deposits, and then re-elevated into land. The river-terraces and lacustrine marls formed before the time

of Julius Cæsar could not be distinguished by any fossil tests from those laid down in the days of Victoria, unless, indeed, traces of human implements were obtainable whereby the progress of civilization during 2000 years might be indicated. So far as regards the shells, bones, and plants preserved in the various formations, it would be absolutely impossible to discriminate their relative dates; they would be classed as "geologically contemporaneous," that is, as having been formed during the same period in the history of life in the European area; yet there might be a difference of 2000 years or more between many of them. Strict contemporaneity cannot be asserted of any strata merely on the ground of similarity or identity in fossils.

But the phrase "geologically contemporaneous" is too vague to have any chronological value except in a relative sense. To speak of two formations as "contemporaneous," which may have been separated by thousands of years, seems rather a misuse of language, though the phraseology has now gained such a footing in geological literature as probably to be inexpugnable. If we turn again for suggestions to the existing distribution of life on the earth (though it is probable that formerly, and particularly among the earlier geological periods, there was considerably greater uniformity in zoological distribution than there is now), we learn that similarity or identity of species and genera holds good, on the whole, only for limited areas, and consequently, if applied to wide geographical regions, ought to be an argument for diversity rather than for similarity of age. If we suppose the British seas to be raised into dry land, so that the organic relics, preserved in their sands and silts, could be exhumed and examined, a general type or common facies would be found, though some species

would be more abundant in or entirely confined to the north, while others would show a greater development in the opposite quarter. Still, there would be such a similarity throughout the whole, that no naturalist would hesitate to regard the organisms as those of one biological province, and belonging to the same great geological period. The region is so small, and its conditions of life so uniform and uninterrupted, that no marked distinction can be drawn between the forms of life in its different parts.

Widening the area of observation, we perceive that as we recede from any given point on the earth's surface the existing forms of life gradually change. Vegetation alters its aspect from climate to climate, and with it come corresponding transformations in the characters of insects, birds, and wild animals. A lake-bottom would preserve one suite of organisms in England, but a very different group at the foot of the Himalaya Mountains, yet the deposits at the two places might be absolutely coeval, even as to months and days. If, therefore, in the geological past there has been, as there is now, a grading of plants and animals in great biological provinces, marked off by differences of contour, climate, and geological history, we must conclude that, while strict contemporaneity cannot be predicted of deposits containing the same organic remains, it may actually be true of deposits in which they are quite distinct.[23]

If, then, at the present time, community of organic forms, except in the case of some almost world-wide spe-

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[23] The present geographical distribution of plants and animals has a profound geological interest, but cannot be properly discussed in this volume. The student will find it luminously treated in Darwin's "Origin of Species," chaps. xii. and xiii.; Lyell's "Principles of Geology," chaps. xxxviii.-xli.; and in Wallace's "Geographical Distribution of Animals," 2 vols. 1876, and his "Island Life," 1880.

cies, obtains only in restricted districts, regions, or provinces, it may have been more or less limited also in past time. Similarity or identity of fossils among formations geographically far apart, instead of proving contemporaneity, may be compatible with great discrepancies in the relative epochs of deposit. For, on any theory of the origin of species, the spread of a species, still more of any group of species, to a vast distance from the original centre of dispersion, must in most cases have been inconceivably slow. It doubtless occupied so prolonged a time as to allow of almost indefinite changes in physical geography. A species may have disappeared from its primeval birthplace, while it continued to flourish in one or more directions along its outward circle of advance. The date of the first appearance and final extinction of that species would thus differ widely, according to the locality at which we might examine its remains.

The grand march of life, in its progress from lower to higher forms, has unquestionably been broadly alike in all quarters of the globe. But nothing seems more certain than that its rate of advance has not everywhere been the same. It has moved unequally over the same region. A certain stage of progress may have been reached in one quarter of the globe many thousands of years before it was reached in another; though the same general succession of organic types might be found in each region. At the present day, for example, the higher fauna of Australia is more nearly akin to that which flourished in Europe far back in Mesozoic time than to the living fauna of any other region of the globe. There seems also to be now sufficient evidence to warrant the assertion that the progress of terrestrial vegetation has at some geological periods and in some regions

been in advance of that of the marine fauna (see p. 1111). Hence arise glaring anomalies in the attempts to group the geological formations of distant countries in conformity with European standards. As Mr. Blanford has well remarked, "in instances of conflicting evidence between terrestrial or freshwater faunas and floras on the one side, and marine faunas on the other, the geological age indicated by the latter is probably correct, because the contradictions which prevail between the evidence afforded by successive terrestrial and freshwater beds are unknown in marine deposits; because the succession of terrestrial animals and plants in time has been different from the succession of marine life; and because in all past times the differences between the faunas of distant lands have probably been, as they now are, vastly greater than the differences between the animals and plants inhabiting the different seas and oceans." [24]

Notwithstanding such exceptions, it may be asserted that in every country where the fossiliferous geological formations are well displayed and have been properly examined, a similar general order of organic succession can be made out among them. Their relative age within a limited geographical area can be demonstrated by the law of superposition. When, however, the rocks of distant

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[24] Mr. Blanford, in his suggestive address to the Geological Section of the British Association at the Montreal meeting, from which the above quotation is taken, gives some examples of the contradictions involved in attempts to correlate distant deposits by means of land and freshwater faunas and floras. The Damuda beds of India, as he points out, contain a flora with middle Jurassic affinities, but the fauna of the overlying Panchet beds is rather Triassic or even Permian. Still more striking is the example furnished by the Lower Coal-measures of New South Wales, where plants which botanists unhesitatingly pronounced to be of Jurassic types are found in the same stratified deposits with undoubted Carboniferous Limestone marine organisms (Orthoceras, Conularia, Spirifer, Fenestella, etc.) Mr. Blanford has returned to this subject in his presidential addresses to the Geological Society. Quart. Journ. xlv. 1889, p. 72, xlvi. 1890, p. 104.

countries are compared, all that we can safely affirm regarding them is that those containing the same or a representative assemblage of marine organic remains belong to the same epoch in the history of biological progress in each area. They are *homotaxial*; but we cannot assert that they are contemporaneous unless we are prepared to include within that term a vague period of many thousands of years.

3. Imperfection of the Geological Record.[25] —Since the statement was made by Darwin, geologists have more fully recognized that the history of life has been very imperfectly preserved in the stratified parts of the earth's crust. Apart from the fact that, even under the most favorable conditions, only a small proportion of the total flora and fauna of any period would be preserved in the fossil state, enormous gaps occur where, from non-deposit of strata, no record has been preserved at all. It is as if whole chapters and books were missing from a historical work. But even where the record may originally have been tolerably full, powerful dislocations have often thrown considerable portions of it out of sight. Sometimes extensive metamorphism has so affected the rocks that their original characters, including their organic contents, have been destroyed. Oftenest of all, denudation has come into play, and vast masses of strata have been entirely worn away, as is shown not only by the erosion of existing land-surfaces, but by the abundant unconformabilities in the structure of the earth's crust.

While the mere fact that one series of rocks lies unconformably on the denuded surface of another, proves the

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[25] See p. 1121.

lapse of an interval between them, the relative length of this interval may sometimes be demonstrated by means of fossil evidence, and by this alone. Let us suppose, for example, that a certain group of formations has been disturbed, upraised, denuded, and covered unconformably by a second group. In lithological characters, the two may closely resemble each other, and there may be nothing to show that the gap represented by their unconformability is of an important character. In many cases, indeed, it would be quite impossible to pronounce any well-grounded judgment as to the length of interval, even measured by the vague relative standards of geological chronology. But if each group contains a well-preserved suite of organic remains, it may not only be possible, but easy, to say how much of the known geological record has been left out between the two sets of formations. By comparing the fossils with those obtained from regions where the geological record is more complete, it may be ascertained, perhaps, that the lower rocks belong to a certain platform or stage in geological history which, for our present purpose, we may call D, and that the upper rocks can, in like manner, be paralleled with stage H. It would be then apparent that, at this locality, the chronicles of three great geological periods, E, F, and G, were wanting, which are elsewhere found to be intercalated between D and H. The lapse of time represented by this unconformability would thus be equivalent to that required for the accumulation of the three missing series in those regions where, sedimentation having been more continuous, the record of them has been preserved.

But fossil evidence may be made to prove the existence of gaps which are not otherwise apparent. As has been

already remarked, changes in organic forms must, on the whole, have been extremely slow in the geological past. The whole species of a sea-floor could not pass entirely away, and be replaced by other forms, without the lapse of long periods of time. If, then, among the conformable stratified deposits of former ages, we encounter abrupt and important changes in the facies of the fossils, we may be certain that these must mark omissions in the record, which we may hope to fill in from a more perfect series elsewhere. The striking palæontological contrasts between unconformable strata are sufficiently explicable. It is not so easy to give a satisfactory account of those which occur where the strata are strictly conformable, and where no evidence can be observed of any considerable change of physical conditions at the time of deposit. A group of quite conformable strata, having the same general lithological characters throughout, may be marked by a great discrepancy between the fossils of the upper and the lower part. A few species may pass from the one into the other, or perhaps every species may be different. In cases of this kind, when proved to be not merely local but persistent over considerable areas, we must admit, notwithstanding the apparently undisturbed and continuous character of the original deposition of the strata, that the abrupt transition from the one facies of fossils to the other represents a long interval of time which has not been recorded by the deposit of strata. Sir A. C. Ramsay, who called attention to these gaps, termed them "breaks in the succession of organic remains."[26] They occur abundantly among the European Palæozoic and Secondary rocks, which, by means of them,

[26] Q. J. Geol. Soc. xix. xx. Presidential Addresses.

can be separated into zones and sections. But though traceable over wide regions they were probably not general over the whole globe. There have never been any universal interruptions in the continuity of the chain of being, so far as geological evidence can show. The breaks or apparent interruptions no doubt exist only in the sedimentary record, and may have been produced by geological agencies of various kinds, such as cessation of deposit from failure of sediment owing to seasonal or other changes; alteration in the nature of the sediment or character of the water; variations of climate from whatever cause; elevation or subsidence by subterranean movements, bringing successive submarine zones into less favorable conditions of temperature, etc.; and volcanic discharges. The physical revolutions, which brought about the breaks, were no doubt sometimes general over a whole zoological province, more frequently over a minor region. Thus, at the close of the Triassic period the inland basins of central, southern and western Europe were effaced, and another and different geographical phase was introduced which permitted the spread of the peculiar fauna of the "Avicula contorta zone" from the south of Sweden to the plains of Lombardy, and from the north of Ireland to the eastern end of the Alps. This phase in turn disappeared to make way for the Lias with its numerous "zones," each distinguished by the maximum development of one or more species of ammonite.[27] These successive geographical revolutions must, in many cases, have caused the complete extinction of genera and species possessing a small geographical range.

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[27] Consult on this subject the memoirs on Jurassic Geography of the late Prof. Neumayr, quoted ante, p. 1086.

cal composition from thoroughly acid materials (granites, felsites, etc.) to basic or even what are called "ultra-basic" compounds (peridotites, serpentines). Though sometimes amorphous over considerable spaces, and then not to be distinguished from ordinary igneous eruptive masses, they for the most part present a more or less distinctly schistose or foliated structure, some of their most abundant and conspicuous members being gneisses, often so coarsely banded as to pass into granite.

The infra-position of these crystalline rocks, combined with their prevalent stratified appearance, naturally led to their being regarded as the oldest known formation on which all the later portions of the terrestrial crust rest. But recent observations have proved many gneisses to be originally igneous rocks, sometimes even intrusive, and therefore younger in date than the rocks which they pierce (pp. 321, 1021). Where the area in which these ancient mineral masses are exposed is small, and especially where only the gneissic or schistose portion of them is seen, the oldest fossiliferous rocks may lie on them with a strong unconformability. The contrast in such conditions between the stratified conglomerates, sandstones, and shales of the Palæozoic series, and the gnarled crystalline gneisses below them is so striking as to have suggested the idea that in these gneisses we have reached the lowest and earliest part of the earth's crust. Hence arose such names as Fundamental gneiss, Urgneiss or Urgebirge.

No portion of the Geological Record has in recent years been more diligently studied than the crystalline schists, which, underlying the vast pile of fossiliferous systems, have been regarded as the earliest surviving chronicles of the history of the earth. But the problems presented by

classification of these rocks. Thus, a particular stratum may be ascertained to be marked by the occurrence in it of various fossils, one or more of which may be distinctive, either from occurring in no other bed above and below, or from special abundance in that stratum. These species may, therefore, be used as a guide to the occurrence of the bed in question, which may be called by the name of the most abundant species. In this way, a geological horizon or zone is marked off, and geologists thereafter recognize its position in the geological series. But before such a generalization can be safely made, we must be sure that the species in question really never does characterize any other platform. This evidently demands wide experience over an extended field of observation. The assertion that a particular species or genus occurs only on one horizon, or within certain limits, manifestly rests on negative evidence as much as on positive. The palæontologist who makes it cannot mean more than that he knows the species or genus to lie on that horizon, or within those limits, and that, so far as his own experience and that of others goes, it has never been met with beyond the limits assigned to it. But a single instance of the occurrence of the fossil in a different zone would greatly damage the value of his generalization, and a few such cases would demolish it altogether. The genus *Arethusina*, for example, had long been known as a characteristic trilobite of the lower zones of the third or highest fauna of the Bohemian Silurian basin. So abundant is one species (*A. Konincki*) that Barrande collected more than 6000 specimens of it, generally in good preservation. But no trace of it had ever been met with toward the upper limit of the Silurian fauna. Eventually, however, a single specimen of a species so nearly identical as to be readily pro-

the original order of succession among the crystalline schists of a particular region, it is even more difficult to form a satisfactory judgment as to the stratigraphical relations of the schists of two detached regions. There is usually no common basis of comparison between them, except similarity of mineral character and structure. But as it can be shown that even in a single area the crystalline schists may sometimes represent the results of many successive operations continuing through a long series of geological periods, it is obvious that the task of correlating these rocks in distinct, and especially in widely separated, areas must be beset with almost insuperable obstacles.

Though in many countries a complete break occurs between the lowest gneisses and the overlying Palæozoic sedimentary formations, there are other regions in which these gneisses are intimately associated with schists, limestones, quartzites, and conglomerates. The real character of this association has been variously interpreted, but on any explanation, it shows that such gneisses cannot be older than certain crystalline masses which may be regarded as probably, if not certainly, of sedimentary origin. Hence, while the inference from one series of sections has been that the gneisses belong to an early condition of the cooling crust of the globe, from another series it has been in favor of these gneisses and their associated sedimentary materials having been formed after the crust was solidified, and after mechanical and chemical sediments had begun to be accumulated.

Taking the widest view of the whole series of pre-Palæozoic rocks, with their vast piles of various sedimentary formations above, and their complex series of crystalline massive and schistose rocks below, we encounter a somewhat serious difficulty in the attempt to group the whole of this

varied assemblage of mineral masses under some common generally applicable stratigraphical name. Such a name has usually been held to imply that the rocks which it designates belong to one well-defined portion of the Geological Record. But this implication is one which every geologist who has worked among these ancient rocks would earnestly deprecate, for he has in some measure realized how vast, varied, and long-continued were the geological changes of which they are the memorials. These mutations include many transformations of the earth's surface, many disturbances of its crust, with enormous denudation and sedimentation, comparable with, if not greater than, those which in later ages were repeated again and again, even after the older fossiliferous formations were laid down. So similar have been the results that it is now difficult, or impossible, to discriminate between the more ancient and the more recent operations. To class all the crystalline schists and the great piles of sedimentary and igneous materials into which they seem to pass, by one general name, after the type of "Cambrian," "Silurian," or "Devonian," may be convenient, but in the present state of our knowledge is apt to lead to confusion, by placing together masses which may be of widely different geological ages and of wholly dissimilar origin. Various terms have been proposed for this complex assemblage of rocks, such as Primitive, Proterozoic, Azoic, Agnotozoic or Archæan. But from the data adduced in Book IV. Part VIII. regarding regional metamorphism, the student will understand how full of uncertainty must be the geological age of many areas of crystalline schists. Mere lithological characters afford no perfectly reliable test of relative antiquity. To prove that any region of crystalline schists may be "Primitive," "Azoic," or "Archæan" we

be traceable as we recede from their original geographical province.

§ v. **Bearing of Palaeontological data upon Evolution.**—Since the researches of William Smith at the end of last century, it has been well understood that the stratified portion of the earth's crust contains a suite of organic remains in which a gradual progression can be traced, from simple forms of invertebrate life among the older rocks to the most highly differentiated mammalia of the present time. Until the appearance of Darwin's "Origin of Species" in 1859, the significance of this progression and its connection with the biological relations of existing faunas and floras were only dimly perceived, though Lamarck had proposed a theory of development, in support of which appeals had been made to the organic succession revealed by the geological record. Darwin, arguing that, instead of being fixed or but slightly alterable forms, species might be derived from others, showed that processes were at work, whereby it was conceivable that the whole of the existing animal and vegetable worlds might have descended from, at most, a very few original forms. From a large array of facts, drawn from observations made upon domestic plants and animals, he inferred that, from time to time, slight peculiarities due to differences of climate, etc., appear in the offspring which were not present in the parent, that these peculiarities may be transmitted to succeeding generations, especially where from their nature they are useful in enabling their possessors to maintain themselves in the general struggle for life. Hence varieties, at first arising from accidental circumstances, may become permanent, while the original form from which they sprang, being less well adapted to hold its

adoption of any general terminology that would involve assumptions as to their definite place and sequence in the geological record, their mode of origin, their relation to the history of plant and animal life, or their identification in different countries.

As an illustration of the danger of such assumptions, I may refer to the history of the investigation of the Laurentian rocks of Canada. From the early observations of Sir W. Logan and Mr. Alexander Murray these rocks came to be regarded as types of the oldest gneisses of the globe. They were looked upon as probably metamorphosed marine sediments that had formed the solid platform on which the whole series of fossiliferous systems of North America had been deposited. The name Laurentian applied to them was transferred to similar rock-masses in other parts of the globe, and came to be accepted as the designation of the oldest known zone in the crust of the earth. But eventually it was discovered by Mr. Lawson that some part, at least, of the Laurentian gneiss is essentially of igneous not of sedimentary origin, and is actually intrusive into what are undoubtedly sedimentary strata. It could not, therefore, itself as a whole be the oldest rock; and all the generalizations and identifications founded on its supposed position fell to the ground. The term Laurentian cannot henceforth have more than a local significance. It serves to designate certain ancient crystalline rocks of Canada, but a geologist would not now employ it to denote any of the rocks of another region, even though they might present similar general lithological characters. We must in the meanwhile be content to restrict the application of such names to the regions in which they originated. There will be much less impediment to the progress of investi-

gation by the multiplication of local names than by the attempt to force identifications for which there is no satisfactory basis. Each country will have its own terminology for pre-Cambrian formations, until some way is discovered of correlating these formations in different parts of the globe.

Although where the stratigraphical succession is most complete the gneisses that rise from under the oldest sedimentary rocks have been found to pierce these rocks, and thus to be of later date; yet in most regions no such proof of posteriority is to be seen. The coarse banded gneisses are usually the foundations on which the stratified fossiliferous formations unconformably rest. There is thus an obvious advantage in treating these gneisses first in an account of pre-Cambrian rocks. I shall here follow this arrangement, and reserve for a later section a description of the sedimentary and igneous formations which intervene between the gneisses and the base of the Cambrian system.

1. *The lowest gneisses and schists*

It has often been remarked that one of the most singular features about the oldest known crystalline rocks is the sameness of their general mineral characters in all parts of the earth. Sedimentary formations constantly vary from country to country, but when we descend beneath their lowest members we come upon a wholly different group of rocks which retain with remarkable uniformity one general type of structure and composition. These rocks include massive materials such as granite, syenite, gabbro, diorite, and hornblende-rock. But even in these a tendency to a schistose arrangement can usually be observed. By far the most generally prevalent structure is a more or less

definite foliation. In the coarse varieties it is marked by alternate bands of distinct mineral characters, orthoclase, plagioclase (commonly an acid variety), quartz, hornblende and mica (white and black) being universally conspicuous. Such rudely foliated rocks are known as coarsely-banded gneisses, and offer gradations into masses which cannot be distinguished from ordinary eruptive material. The banding is sometimes strongly marked by the separation of the more silicated from the less silicated minerals, as where layers of felspar or of quartz alternate with others of hornblende, pyroxene or biotite.

While the foliated structure and the arrangement of the minerals in parallel bands gives a bedded aspect to these rocks, the resemblance of this structure to the true bedding of detrital materials is probably more apparent than real. A little examination shows that the layers are not persistent, that they cross each other, and that portions of one may be entirely separated and inclosed within another. Whatever may have been their origin they have certainly undergone enormous mechanical compression and deformation. They have been plicated, rolled out, dislocated, and crumpled again and again. Hence, though for short distances it is possible to separate out layers or bosses of felspathic, hornblendic, pyroxenic, peridotitic, or serpentinous composition from the general body of gneiss, the geologist who tries to fix definite stratigraphical horizons by this means soon abandons the attempt in despair, and comes to the conclusion that no sequence of a trustworthy nature can be established in the body of the gneiss itself.

From the coarsest gneisses gradations may be traced to fine silky schists; and this not only on a large scale in tracts capable of being delineated on a map, but on so small

a scale as to be illustrated even in hand-specimens. Such transitions seem to arise from the different effects of mechanical deformation on materials that offered considerable differences in lithological composition and structure. Fine talcose schists, for example, can be traced to original peridotites; hornblendic and actinolitic schists to such rocks as gabbro, diorite, or dolerite.

In the older accounts of these rocks the gneisses are described as passing into or alternating with a wholly different type of rocks, among which may be included limestone (sometimes strongly graphitic), dolomite, quartzite, graphite-schist, mica-schist and other varieties of schistose material. This apparent gradation was believed to mark an original transition of the sediment out of which the gneiss was thought to have been formed into the calcareous, argillaceous, or carbonaceous sediment, which was the earliest condition of the associated limestones and schists. It was thus looked upon as evidence that the whole crystalline series represented, in a metamorphosed state, an ancient accumulation of sedimentary materials. The existence even of organic remains in the limestone was insisted upon, and the so-called *Eozoon* was cited as the most ancient relic of animal life.[3] But there is now every reason to believe such gradations to be generally deceptive. As a result of the enormous mechanical compression and deformation which these ancient rocks have undergone, igneous and aqueous materials have been so plicated and crushed together and have undergone such profound metamorphism, that it is sometimes hardly possible to trace a boundary between them. There seems no

[3] See on this subject postea, pp. 1160, 1161, and authorities there cited.

reason to look upon the limestones, argillites, quartzites, and schists as other than intensely altered sediments, which in theory, if not in actual practice on the ground, must be separated from the gneisses.

Among the various theories which have been proposed to account for the genesis of the lowest gneisses and schists, three deserve particular mention here. (1) These rocks are by some geologists believed to be a portion of the original crust which solidified on the surface of the globe. (2) They are by others held to be ancient sedimentary rocks in a metamorphosed condition, and in some parts so changed as to have been actually melted and converted into intrusive material. (3) They are believed by yet another class of observers to be essentially eruptive rocks, and to be comparable with the deeper seated or plutonic portions of such igneous rocks as may be seen to traverse the earth's crust.

(1) From the ubiquity of their appearance, the persistence of their striking lithological characters, and especially the curious apparent blending in them of the igneous and sedimentary types of structure, the idea not unnaturally arose that the lowest crystalline rocks represent the first crust that formed on the surface of the globe.[4] These rocks have been supposed to include some of the early surfaces of consolidation of the molten globe, and some of the first sediments that were thrown down from the hot ocean which eventually condensed upon the planet. Such a speculative view of their origin may seem not incredible in regions where these ancient crystalline rocks are covered unconformably

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[4] See Credner's "Geologie," vi. *b*. Die Fundamental Formation; Erstarrungskruste. Compare also Rosenbusch, Neues Jahrb. 1889, vol. ii. p. 81.

by the oldest Palæozoic formations, from which they are marked off by so striking a contrast of structure and composition, and to which they have contributed so vast an amount of detrital material. But it must be tested by the evidence of the rocks themselves, not only where the geological record is confessedly incomplete, but where it is comparatively full. Nowhere among the lowest gneisses is any structure observable which can be compared with the superficial portion of a lava that cooled at the surface. On the contrary, the analogies they furnish are with deep-seated and slowly-cooled sills and bosses. The supposed intercalation and alternation of limestone and other presumably sedimentary materials in the old gneisses are probably all deceptive. In some regions they can be shown to be so, and it can there be demonstrated that the gneisses are really eruptive rocks which pierce the adjacent sedimentary or schistose masses, and are thus of younger age than these. If this relation can be clearly established in regions where the evidence is fullest, it is obviously safe to infer that a similar relation might be discoverable if the geological record were more complete, even in those parts of the world where the break between the lowest gneisses and the Palæozoic formations seems to be most pronounced. At least the possibility that such may be the case should put us on our guard against adopting any crude speculation about the original crust of the earth.

The present condition of these ancient rocks differs much from that which they originally possessed. In particular they have undergone enormous mechanical deformation, have been to a large extent crushed and recrystallized, and have acquired a marked schistose structure. But in every large region where they are developed we may obtain

evidence to connect them with plutonic intrusions, not with superficial consolidation, and to show that many of their essential details of structure may be paralleled among much later crystalline schists produced from the metamorphism of Palæozoic sediments and igneous rocks.

(2) That the lowest gneisses of Canada and other regions are metamorphosed sedimentary rocks was believed by probably most geologists until only a few years ago. But the increased attention which has been given to the study of the subject since Prof. Lehmann's great work on the Saxon gneisses appeared in 1884, has led to so complete a revolution of opinion that this belief, at least in its original form, is now almost wholly abandoned. Those who still hold it in a modified shape recognize that the original sediments must have differed considerably from those of any recognizably sedimentary formation, and were probably deposited under peculiar conditions. They admit that these rocks have undergone extreme metamorphism, and that the alteration of them has been carried so far as to reduce them in some places to an amorphous crystalline condition which cannot be distinguished from that of normal eruptive material. It has been maintained, indeed, that the Laurentian gneisses of Canada have been produced by the actual fusion of the older sedimentary pre-Cambrian formations and the absorption of these rocks into the general magma of eruptive material which now appears as gneiss.[5] The intrusive character of some of the gneiss, which might be regarded as proof of its really igneous origin, is accounted for by what is called an "aquo-igneous fusion" of some parts of the sedimentary rocks and their intrusion into less completely metamorphosed portions of the series.

[5] A. C. Lawson, Annual Report Canadian Geol. Surv. 1887.

(3) Probably the great majority of geologists now adopt in some form the third opinion, that the oldest or so-called "Archæan" gneisses are essentially eruptive rocks, and that they should be compared with the larger and more deeply-seated bosses of intrusive material now visible on the earth's surface. Whether they were portions of an original molten magma protruded from beneath the crust, or were produced by a re-fusion of already solidified parts of that crust or of ancient sedimentary accumulations laid down upon it, must be matter of speculation. In the gathering of actual fact we cannot go beyond their character as eruptive rocks, which is the earliest condition to which they can be traced, and we must consequently place them in the same great series as all the later eruptive materials with which geology has to deal. It is quite true that they have been profoundly modified since their original extrusion, but traces of their original character as masses of mobile, slowly crystallizing and segregating material have not been entirely effaced.

Looking at the gneisses as a whole, with their various accompaniments, we find them to form a complex assemblage of crystalline rocks which, though generally presenting a foliated structure, pass occasionally into the amorphous condition of ordinary eruptive rocks. In composition they range from granite at the one end to peridotites and serpentines at the other. Hand-specimens of these rocks in their amorphous or unfoliated condition do not differ in any essential feature from the material of ordinary intrusive bosses in later portions of the terrestrial crust, and the same similarity of structure is borne out when thin slices are placed under the microscope.

Perhaps the most convincing proof of the really eruptive nature of the gneisses is to be found in those tracts where

they have undergone least disturbance, and where therefore the way in which they traverse the adjacent rocks can be distinctly perceived. They are there seen to cross many successive zones of sedimentary material, to send out veins and protrusions, and to inclose portions of the adjacent rocks, while at the same time the surrounding masses present many of the familiar features of contact-metamorphism. Sections where these phenomena can be satisfactorily observed are no doubt comparatively rare, for in general the rocks have been so crushed and recrystallized that their original relations have been destroyed. It is in consequence of these subsequent movements that so much difficulty has been found in determining the igneous nature of the gneisses and their intrusive character with reference to the rocks adjacent to them. The abundant veins which, as in ordinary granite bosses, proceeded from the original gneiss have been compressed into long parallel bands which seem to alternate with the schists among which they were injected, while portions of the surrounding rock inclosed within the gneiss have had a foliation superinduced upon them parallel to that of these bands. Any one who first studied the older rocks where such structures are visible might easily be deceived into the belief that these alternations of parallel strips of gneiss and schist, or gneiss and limestone, really represented a continuous sequence of sedimentary material. Nor would he readily perceive his mistake until he could trace the junction-line into some tract where, by cessation of the deformation, the original relation of the two groups of rocks could be observed.[6]

It is not difficult to obtain conclusive proof that in the

[6] See A. C. Lawson, Bull. Geol. Soc. Amer. i. 1890, p. 184.

complex assemblage of rocks constituting the lowest gneiss there are not only differences of composition and structure, but also differences of relative age. Some portions of the series can be distinctly seen to have been intruded into others. True dikes can be traced among them both of acid and basic composition. In the northwest of Scotland, for example, the general body of gneiss is traversed by a multiplicity of dikes, cutting across the oldest foliation of the gneiss in a general northwesterly direction. A detailed study of such an area reveals the fact that the fundamental rocks represent a prolonged series of igneous protrusions. As this complicated mass of eruptive material has subsequently undergone profound alteration by dynamo-metamorphism, the difficulties in unravelling its history need cause no surprise.

Leaving out of account the dikes which undoubtedly mark later injections of igneous material, and confining our attention to the general mass of gneiss in its variations from an amorphous or granitoid condition through the coarse banded varieties to the finer schistose types, we may pursue the history of these puzzling rocks by comparing them with the larger intrusive bosses and sills that have accompanied the volcanic eruptions of all geological periods. In these deep-seated and slowly cooled masses of igneous material, as has already been pointed out (p. 962), we may frequently observe evidence of the segregation of the component minerals in bands or irregular patches. Such a segregation seems to have taken place sometimes after the erupted rock had come to rest, sometimes while it was still in movement. In the latter case the layers of separated materials may sometimes have been dragged forward so as to acquire a somewhat banded or streaky structure. How far

the characteristic arrangements of the minerals in the coarse banded gneisses may have arisen from a process of this kind in the consolidation of originally eruptive materials, remains still an open question, though the progress of research favors the idea that such has really been to a large extent their source.[7]

It is certain, however, that, besides the original banded and probably segregated structure, the gneisses, as the result of much mechanical deformation, have had other and later structures superinduced upon them, sometimes at successive periods of disturbance. The most massive granitoid rocks have thus been crushed down under great strain, and have recrystallized as fine granulitic gneiss or mica-schist. Epidiorites and amphibolites have by a similar process been converted into hornblende-schists. In these cases the reconstructed rocks usually exhibit a finely schistose structure, quite distinct from that of the parent mass, but with no markedly banded arrangement. Occasionally, however, in the recrystallization of the materials, segregation into more or less definite layers or centres has come into play, so that in this obviously secondary arrangement a certain resemblance may be traced, though on a small scale, to the much coarser bands in the earliest remaining condition of the oldest gneisses.

There is yet another source of difficulty in judging of the relative age and origin of various structures among the crys-

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[7] This inference applies more particularly to the coarsely banded gneisses where the individual layers, consisting in great part of different minerals, resemble some of the segregation bands in eruptive masses (p. 1021). There can be little doubt that, as already remarked, the efficacy of mechanical deformation as a factor in the production of gneisses has been pushed too far. It will account for the crushed granulitic and schistose condition, but hardly for the coarsely banded structure, where the layers consist of very different mineral aggregates.

into such fine particles as to remain in mechanical suspension in the water. Such obdurate varieties must be examined in bulk. In the Carboniferous system, the shales that boil down completely are those in which their component argillaceous particles have been compacted merely by pressure, or with such slight cementation as could be destroyed by boiling. They are usually gray beds, such as so often accompany limestones. The black shales, on the other hand, containing a considerable proportion of bituminous cement, will not thoroughly break up even after prolonged boiling.

The drying and steeping here described may be regarded as processes of rapid artificial weathering. The effects of the heat of a fire upon shale resemble those of the sun's rays, and the soaking in water is a counterpart of the action of rain. It is surprising how easily hard, compact shale, which can with difficulty be broken or split with a hammer, may, by the method above specified, be reduced to dust or to fine granular débris, from which even delicate shells may easily be picked out entire. One may thus experimentally learn how important a part in the disintegration of rocks must be taken by the alternate desiccation and saturation of their surfaces by sunshine and shower.

Limestone and Ironstone.—Among fossiliferous limestones, remarkable differences are observable in the lithological condition of the inclosed fossils, and in the ease with which they can be recognized and extracted. It is only by diligent practice that these peculiarities can be so mastered as to enable the observer to make an exhaustive collection from the rocks which he explores. In some limestones, the organic remains are specially abundant in particular layers or pockets. Fragments of these parts of the rock may be taken home, and their fossils may be extracted by fixing the block on a piece of lead 1 inch thick and about 6 inches square, and cutting out the desired specimens with hammer and chisel. Entomostraca, and other small organisms in which the valves are united, may also be obtained in a perfect condition from this class of rocks, by pounding fragments of the fossiliferous material with a hammer within the circle of a small iron ring or "washer," one-eighth of an inch in thickness. As the rock is crushed by the blows of the hammer the organisms jump out of the matrix, but are retained within the bounds of the ring, which also answers as a gauge, preventing the material from being broken too small. The pounded rock is afterward washed free from dust, dried and searched as above directed. Many limestones reveal their fossils best

have indeed a clew to their relative age; but such evidence carries us but a small way. The gneisses where obviously intrusive are indisputably of eruptive origin, but they alternate with finely schistose bands which sometimes seem to cut them. The bedding or banding of the rocks affords no guide whatever as to sequence. It has been so folded and crumpled that even if it represented original stratification it could probably never be unravelled. But there is every reason to believe that it bears no real analogy to stratification. It may sometimes represent, as already stated, layers of segregation and flow-structure in an original igneous magma, at other times planes of movement in the crushing of already consolidated material. But whatever may have been its origin, it remains now in an inextricable complexity. Here and there, indeed, for short distances some well-marked band of rock may be traced, but the various rock-masses generally succeed each other in so rapid and tumultuous a manner as to defy the efforts of the field-geologist who would patiently map them.

As a rule, only where the earliest type of gneiss has been invaded by subsequently intruded masses can a successful attempt be made to disentangle the confused structure. Successive systems of dikes may thus be traced, and evidence may be obtained that powerful dynamic stresses affected the rocks between some of these intrusions. The dikes have sometimes been crushed, plicated, and disrupted until they have been reduced to isolated patches of schist irregularly distributed among the reconstructed gneiss. And through these involved and complicated masses newer groups of dikes have risen, to be again subjected to mechanical deformation.

The question may occur to the student whether this com-

plex system of evidently plutonic igneous rocks was ever connected with any superficial volcanic activity. No such connection has yet been definitely ascertained, but it may be regarded as highly probable. If the most ancient gneisses with their dikes and bosses were the deep-seated portions of the successive uprisings of the igneous magma which culminated in volcanic eruptions, we may hope eventually to discover some trace of the materials that were thrown out to the surface and accumulated there. In some of the overlying pre-Cambrian masses of sedimentary rocks abundant lavas, tuffs, and agglomerates have been found, indicating the outpouring of volcanic material at the surface during the deposition of these sediments. The vast scale of these volcanic eruptions may be inferred from the fact that in the Lake Superior region the accumulated materials discharged at the surface attained a thickness which has been estimated at more than six and a half miles. It may be eventually discovered that some of these superficial manifestations of volcanic action have been connected with bosses, sills, or dikes that form part of the body of the gneiss below.

It must be confessed that much detailed work among the lower gneisses in all parts of the world is needed before the many problems which they present are solved. But the following conclusions regarding them may now be regarded as certain:—these rocks are in the main various forms of original eruptive material, ranging from highly acid to highly basic; they form in general a complex mass belonging to successive periods of extrusion; some of their coarse structures are probably due to a process of segregation in still fluid or mobile, probably molten, material consolidating below the surface; their granulitized and schistose characters, and their folded and crumpled structures point to subsequent

intense crushing and deformation; their apparent alternations with limestone and other rocks, which are probably of sedimentary origin, are deceptive, indicating no real continuity of formation, but pointing to the intrusive nature of the gneiss.

2. *Pre-Cambrian sedimentary and volcanic groups*

In different parts of the world enormous masses of rock are now known to intervene between the oldest or "Archæan" gneisses, and the bottom of the fossiliferous series of formations. It was in Canada that these rocks were first studied. Logan and Murray grouped them under the general name of Huronian, and they were believed to fill up the gap between the Laurentian gneiss on the one hand, and the Potsdam sandstone or base of the fossiliferous series on the other. Later more detailed study of these rocks in Canada and the adjoining regions of the United States has shown them to possess even a greater importance than their original discoverers imagined, for they have been found to consist of several distinct groups or systems, attaining a vast thickness and presenting a record of stupendous disturbances, denudations and depositions of sediment, together with memorials of extensive and prolonged volcanic action. In the higher members of these sedimentary deposits, distinct remains of animal life have in several regions been found. There is thus opened out the possibility of the ultimate discovery of a series of fossiliferous formations even below the base of the Palæozoic series.

Where metamorphism has not interfered with the recognition of their original characters, these ancient sedimentary rocks present no structural feature to distinguish them from the detrital accumulations of higher parts of the geological

record. They consist of clays and muds hardened into shales and slates, of sands compacted into sandstones and quartzites, of gravels and shingles solidified into conglomerates. These rocks prove beyond question that the processes of denudation and deposition were already in full operation with results exactly comparable to those of Palæozoic and later time.

Few parts of the stratified crust of the earth present greater interest than these earliest remaining sediments. As the geologist lingers among them, fascinated by their antiquity and by the stubbornness with which they have shrouded their secrets from his anxious scrutiny, he can sometimes scarcely believe that they belong to so remote a part of the earth's history as they can be assuredly proved to do. The shales are often not more venerable in appearance than those of Cambrian or Silurian time, and show as clearly as these do their alternations of finer and coarser sediment. The sandstones display their false-bedding as distinctly as any younger rock, and one can make out the shifting character of the currents and the prevalent direction from which they brought the sand. The conglomerates in their well-rounded fragments tell as distinctly as the shingle of a modern beach of the waste of a land-surface and the pounding action of waves along a shore.

Not only are these structural details precisely similar to those of younger detrital rocks, but we may here and there detect the remains of the pre-Cambrian topography from which these primeval sediments were derived, and on which they were deposited. Hills and valleys, lines of cliff and crag, rocky slopes and undulating hollows have been revealed by the slow denudation of the pre-Cambrian strata under which these features were gradually buried. To this

formability really indicated a longer period than the massive succession of deposits.

6. Fossil evidence furnishes the chief means of comparing the relative chronological value of groups of rock. A break in the succession of organic remains marks an interval of time often unrepresented by strata at the place where the break is found.[3] The relative importance of these breaks, and therefore, probably, the comparative intervals of time which they denote, may be estimated by the difference of the facies of the fossils on each side. If, for example, in one case we find every species to be dissimilar above and below a certain horizon, while in another locality only half of the species on each side of a band are peculiar, we naturally infer, if the total number of species seems large enough to warrant the inference, that the interval marked by the former break was very much longer than that marked by the latter. But we may go further, and compare by means of fossil evidence the relation between breaks in the succession of organic remains and the depth of strata between them.

Three series of fossiliferous strata, A, C, and H, may occur conformably above each other. By a comparison of the fossil contents of all parts of A, it may be ascertained that, while some species are peculiar to its lower, others to its higher portions, yet the majority extend throughout the group. If now it is found that, of the total number of species in the upper portion of A, only one-third passes up into C, it may be inferred with some probability that the time represented by the break between A and C was

[3] See ante, p. 1100, and the classic essays of the late Sir A. C. Ramsay there cited.

really longer than that required for the accumulation of the whole of the group A. It might even be possible to discover elsewhere a thick intermediate group B filling up the gap between A and C. In like manner, were it to be discovered that, while the whole of the group C is characterized by a common suite of fossils, not one of the species and only one half of the genera pass up into H, the inference could hardly be resisted that the gap between the two groups marks the passage of a far longer interval than was needed for the deposition of the whole of C. And thus we reach the remarkable conclusion that, thick though the stratified formations of a country may be, in some cases they may not represent so long a total period of time as do the gaps in their succession—in other words, that non-deposition has been in some areas more frequent and prolonged than deposition, or that the intervals of time which have been recorded by strata have sometimes not been so long as those which have not been so recorded.

In all speculations of this nature, however, it is necessary to reason from as wide a basis of observation as possible, seeing that so much of the evidence is negative. Especially needful is it to bear in mind that the cessation of one or more species, at a certain line among the rocks of a particular district, may mean nothing more than that, owing to some change in the conditions of life or of deposition, these species were compelled to migrate, or became locally extinct, at the time marked by that line. They may have continued to flourish abundantly in neighboring districts for a long period afterward. Many examples of this obvious truth might be cited. Thus, in a great succession of mingled marine, brackish-water, and terrestrial strata, like that of the Carboniferous Limestone series of Scotland,

corals, crinoids, and brachiopods abound in the limestones and accompanying shales, but grow fewer or disappear in the sandstones, ironstones, clays, and bituminous shales. An observer, meeting for the first time with an instance of this disappearance, and remembering what he had read about "breaks in succession," might be tempted to speculate about the extinction of these organisms, and their replacement by other and later forms of life, in the overlying strata. But further research would show him that, high above the plant-bearing sandstones and coals, lie other limestones and shales charged with the same marine fossils as before, and followed by still further groups of sandstones, coals, and carbonaceous beds and yet higher marine limestones. He would thus learn that the same organisms, after being locally exterminated, returned again and again to the same area when the conditions favorable for their migration reappeared and enabled them to reoccupy their former haunts. Such a lesson would probably teach him how largely the fauna entombed and preserved on any particular geological horizon has been influenced by the conditions of sedimentation, and that he should pause before too confidently asserting that the highest bed in which certain fossils can be detected marks really their final appearance in the history of life. An interruption in the succession of fossils may be merely temporary or local, one set of organisms having been driven to a different part of the same region, while another set occupied their place until the first was enabled to return.

The remarkable limitation of certain species to a restricted vertical range in a continuous series of stratified deposits, as in the case of the Silurian graptolites and the Jurassic ammonites already cited, affords a valuable basis

for stratigraphical arrangement and comparison. The succession of these species has been in some cases similar over such wide geographical areas that it is difficult to connect this organic sequence with any physical revolutions, of which indeed in a conformable series of sediments there may be little or no trace. As already suggested there may have been some biological law that governed these apparently rapid extinctions or replacements of organic forms, but which is not yet perceived or understood.

7. The Geological Record is at the best but an imperfect chronicle of the geological history of the earth. It abounds in gaps, some of which have been caused by the destruction of strata owing to metamorphism, denudation, or otherwise, some by original non-deposition, as above explained. Nevertheless it is from this record that the progress of the earth is chiefly traced. It contains the registers of the births and deaths of tribes of plants and animals, which have from time to time lived on the earth. Probably only a small proportion of the total number of species, which have appeared in past time, have been thus chronicled, yet, by collecting the broken fragments of the record, an outline at least of the history of life upon the earth can be deciphered.

It cannot be too frequently stated, nor too prominently kept in view, that, although gaps occur in the succession of organic remains as recorded in the rocks, there have been no such blank intervals in the progress of plant and animal life upon the globe. The march of life has been unbroken, onward and upward. Geological history, therefore, if its records in the stratified formations were perfect, ought to show a blending and gradation of epoch with epoch, so that no sharp divisions of its events could be made. But the

record of the history has been constantly interrupted: now by upheaval, now by volcanic outbursts, now by depression, now by protracted and extensive denudation. These interruptions serve as natural divisions in the chronicle, and enable the geologist to arrange his history into periods. As the order of succession among stratified rocks was first made out in Europe, and as many of the gaps in that succession were found to be widespread over the European area, the divisions which experience established for that portion of the globe came to be regarded as typical, and the names adopted for them were applied to the rocks of other and far distant regions. This application has brought out the fact that some of the most marked geological breaks in Europe do not exist elsewhere, and, on the other hand, that some portions of the record are much more complete there than in other regions. Hence, while the general similarity of succession may remain, different subdivisions and nomenclature are required as we pass from continent to continent.

The smallest and simplest subdivision of the Geological Record is a stratum, layer, seam or bed. As a rule it is distinguishable by lithological rather than palæontological features. Where a bed, or limited number of beds, is characterized by one or more distinctive fossils, it is termed a zone or horizon, and, as already mentioned, is often known by the name of a typical fossil, as the different zones in the Lias are by their special species of ammonite.[3] Two or more such zones, united by the occur-

[3] Prof. Gaudry estimates the total number of zones in the European geological series at 114. In this calculation the Jurassic system is allowed no fewer than 34; the Carboniferous and Permian together, 10; and the Cambrian and Silurian together, 20 ("Enchaînements du Monde Animal: Fossiles Primaires," 1883). Prof. Lapworth has recognized 20 distinct graptolite zones in the Cam-

geological revolutions. Gradations can sometimes be traced, as in the Penokee district of Wisconsin, from graywackes and slates through every stage of increasing metamorphism into mica-schists which present every appearance of complete original crystallization.[21] The limestones have passed into the condition of marbles; the iron ores, probably originally carbonates, have become oxidized into limonite, hæmatite and magnetite, while the ore has been concentrated into separate masses. The "greenstones" have passed into the condition of true schists.[22] Some of these metamorphosed areas present so many points of resemblance to the lower gneisses already described that it is not at all surprising that they should have been confounded, and that their true relations should only have been made out after much controversy and long-continued detailed study.

A great deal of discussion has arisen as to the true relations of these pre-Cambrian stratified and eruptive rocks to the coarse-crystalline banded gneisses above described. In some sections a complete and strong unconformability occurs between the two series, and no doubt can there exist as to the enormous break that separates them. In other regions, however, the lower gneisses are so involved with schists, limestones, and conglomerates that no satisfactory separation of them has been made, while in some places the gneiss actually crosses these rocks intrusively. Each country or district may present its own phase of the problem. At present we have no means of determining the true correlation of the pre-Cambrian rocks in separate and especially in distant areas. If we admit that the lowest

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[22] G. H. Williams, Bull. U. S. Geol. Surv. No. 62, 1890.
[21] R. D. Irving and C. R. Van Hose, 10th Ann. Rep. U. S. Geol. Surv. 1890, p. 434.

gneisses with their accompaniments form an eruptive assemblage of which the component portions may belong to widely different periods of time, it is quite conceivable that a certain group of sedimentary formations may be found in one district to lie unconformably on these gneisses, and in another to be pierced by some of their younger members.

There is likewise some difficulty in fixing the upper limit of the pre-Cambrian formations. Where the Cambrian rocks lie on them unconformably the obvious stratigraphical break forms a convenient line of division. But in some countries a thick mass of conformable sedimentary rocks underlies the *Olenellus*-zone which has been taken as the base of the Cambrian system, and in these instances the line of separation becomes entirely arbitrary. Sections of this nature are of great value, inasmuch as they impress upon the geologist that the artificial character of the divisions by which he classes the geological record is not confined to the fossiliferous formations, but marks also those of the pre-Cambrian series. Unconformabilities, even where widespread, cannot be regarded as universal phenomena, and though of infinite service in classification, should be employed with the full consciousness that the blanks which they represent do not indicate any world-wide interruption of geological continuity, but may at any moment be filled up by the evidence of more complete sections.

With regard to the comparative value of the pre-Cambrian rocks in the chronology of geological history no precise statement can be made. But various circumstances show that they must represent an enormous period of time. We shall see in succeeding pages that from the general character of the Cambrian fauna it must be regarded as certain that life had existed on the earth for a long series

of ages before that fauna appeared, in order that such well-advanced grades of organization should then have been reached. One of the most interesting chapters of geological history would be supplied if some adequate account could be given of the stages of this long pre-Cambrian evolution.

But the mere thickness and variety of the pre-Cambrian formations, together with their unconformabilities and other structural features, suffice to prove that they represent an enormous chronological interval. In North America, where, so far as at present known, they are most extensively developed, they are estimated to attain a thickness of more than 65,000 feet, or upward of twelve miles, and have been regarded there as chronologically quite equal to the whole of the rest of the geological record. Even when we eliminate the bedded volcanic rocks from the computation and reduce the remaining sedimentary series to the lowest allowable dimensions, an enormous mass of stratified material remains, which, even if it had been uninterruptedly deposited, would have required a period of time comparable to probably more than that taken by the whole of the Palæozoic systems. But we know that the deposition was not continuous. Both in North America and in Europe there is clear evidence from marked unconformabilities that it was broken by epochs of upheaval and by long periods of extensive denudation. It is evident, therefore, that we must assign to the records of pre-Cambrian time a far more important chronological value than has generally been apportioned to them.

If, as already stated, it is impossible in the present state of science to find any satisfactory basis for the correlation of the oldest gneisses in distant and disconnected regions, it is not more practicable to establish a basis of correlation

for the pre-Cambrian stratified formations. The evidence of fossils hardly as yet exists, and mere lithological characters are in such circumstances of little value. All that can be done at present is to work out the succession of rocks in each well-defined geographical and geological area, giving local names to the stratigraphical groups or systems that may be established, and trusting to future research for some method of possibly ascertaining the parallelism of these divisions in different parts of the world. Hence in the following summary of the characters of the pre-Cambrian rocks in the Old World and in the New no attempt will be made to adopt any general terminology, but in each country the names and divisions adopted there will be given.

§ ii. Local Development

Britain.—Much attention has been given in recent years to the pre-Cambrian rocks of the British Isles and a voluminous literature has arisen concerning them. Rocks, however, have been claimed as pre-Cambrian which are certainly eruptive masses of later date than parts of the Lower Silurian series. Others have been assigned to a similar position, though their relations to the older Palæozoic rocks cannot be seen; while others again cannot properly be disjoined from the lower portion of the Cambrian system. In the confusion which has thus been introduced it will be most satisfactory to restrict attention to those rocks and areas about the true relations of which there appears to be least room for dispute.

In no part of the European area are rocks of pre-Cambrian age more admirably displayed than in the northwest of Scotland. Their position there, previously indicated by Macculloch[23] and Hay Cunningham,[24] was first definitely

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[23] "A Description of the Western Islands of Scotland," 1819.

[24] "Geognostical Account of the County of Sutherland," Highland Soc. Trans. viii. 1841, p. 73.

Tertiary or Cainozoic (*Continued*)	**Oligocene**—Upper fluvio-marine beds of Isle of Wight; Basalt plateaus of N.W. Europe and Iceland; Rupelian and Tongrian of Belgium, Calcaire de la Beauce, Grès de Fontainebleau, Gypse lacustre, etc.; Brown Coal series of Germany. In France, Belgium, Switzerland, and northern Italy the following subdivisions have been generally adopted: Aguitanian stage; Stampian stage; Tongrain stage, underlain in N. Italy by the Sestain stage.	Oligocene (?)—Vicksburg beds.		
	Eocene—sands and clays of the London and Hampshire basins; Gypsum, Caillasses, Calcaire grossier, etc., of Paris basin; Nummulitic Limestone and Flysch (in part) of Alps and southern Europe; Liburnian stage of eastern Alps.	Eocene—Lignitic sands and clays, Clayborne and Jackson (Alabama) beds of the East—Wahsatch, Green R., Bridger, Uinta formations of the West.	Nari group, Kirthar group, Ranikot beds, Nummulitic beds, etc., of Cutch, Sind, Salt Range, etc.	Mount Brown and Nummulitic beds—Shelly calcareous sandstones, with abundant interbedded volcanic rocks.
Secondary or Mesozoic	**Cretaceous.** Danian—Chalk of Faxoe, Maestricht, Garumnian, Maestrichtian, etc. Senonian—Upper Chalk, Oberer Quadersandstein, Campanian, Santonian. Turonian—Lower Chalk and Chalk-marl; Oberer and Mittlerer Pläner, Hippurite Limestone, Gosau beds, Angoumian, Ligerian. Cenomanian—Upper Greensand, Unterer Pläner, Unterer Quadersandstein, Carentonian, Rothomagian.	Cretaceous—Lignitic or Laramie group. Fox Hills " Colorado " Dakota " } Upper Missouri region and other tracts in the West.	Deccan "traps." Hippurite Limestone of Sind.	Cretaceo-tertiary—including the most valuable coal deposits of New Zealand.
	Albian—Gault Clay. Aptian—Calcaires à Plicatules. Urgonian—Calcaires à *Requienia*. Neocomian—Lower Greensand, Wealden beds, Hauterivian Valenginian.	...	Neocomian of Cutch and Salt Range.	Green and gray sandstones, with bituminous coals on w. coast

Secondary or Mesozoic (*Continued*)	**Jurassic.** Purbeckian. Portlandian. Kimeridgian. Corallian. Oxfordian—Oxford Clay and Kellaways rock (Callovian); Oberer (Weisser) Jura or Malm. Bathonian—Great Oolite, Forest Marble, Cornbrash, Mittlerer Jura or Dogger in part. Bajocian—Inferior Oolite Toarcian—Upper Lias. } Schwarzer Jura or Lias. Liassian—Middle Lias. } Sinemurian—Lower Lias. } Hettangian—Infra-Lias, Angulatus and Planorbis zones of Lower Lias.	The Jurassic system has not yet been abundantly found in North America, but its existence is known by the discovery of characteristic fossils. ...	... Jurassic of Cutch, Salt Range, N.W. Himalayas.	Upper—Mataura beds and coal seams. Middle—Putakaka beds. Lower—Flag Hill beds. Liassic—Catlin's River beds; Bastion beds.
	Triassic. Rhætic. Keuper. Muschelkalk. Bunter.	Trias or Jura-Trias. ...	Trias of N.W. Himalayas and Salt Range. The Gondwána system appears to represent the whole succession of deposits from early Palæozoic to Jurassic time.	Rhætic and Triassic—Otapiri beds; Wairoa beds. Oreti beds, with great conglomerate and sandstone.
Primary or Palæozoic	**Permain** or Dyas. Zechstein—Magnesian Limestone, Marl-slate, Kupferschiefer. Rothliegendes—Red Sandstones, Conglomerates, Breccias.	Permian or Permo-Carboniferous.		Kaihiku series—Conglomerates, sandstones, etc.
	Carboniferous. Coal-Measures—Terrain Houiller, Steinkohlen-formation. Millstone Grit—Flötzleerer Sandstein. Carboniferous Limestone Series—Calcaire Carbonifère, Kohlenkalk, Kulm.	Coal-Measures, Carboniferous. Sub-Carboniferous.		Lower Carboniferous and Upper Devonian—Maitai slates; Te Anau beds.

(over)

hornblende, and magnetite, sometimes with blue opalescent quartz, and sometimes with black mica. These predominant minerals are sometimes distributed quite without structure, so that the rock appears as a syenite, diorite, gabbro, peridotite, picrite, pyroxene-granulite, or other massive amorphous member of the eruptive rocks. From these structureless areas, which probably represent most nearly the original condition of the materials, gradations can be traced into well foliated masses, and into coarsely banded gneisses, where the minerals have segregated into lenticular bands and elliptical or irregular concretions. Though it

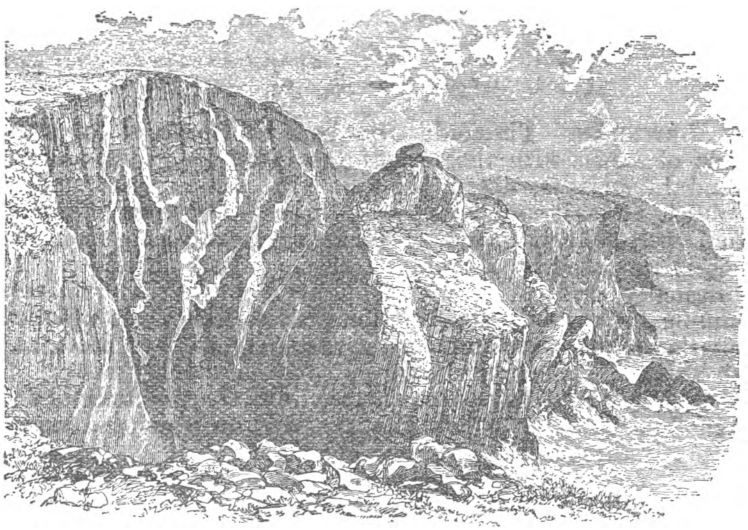

Fig. 326.—Veins of pegmatite in gneiss, south of Cape Wrath.

may often be difficult in practice to distinguish types of structure among these rocks, two such types may in many instances be recognized. In the first place, there is the banded or segregated structure, in which the predominant minerals have separated out from each other, and have crystallized more or less apart, often in coarse aggregations, forming in this way distinct bands or folia which, since they are often crossed by the planes of foliation, are evidently older than the development of these planes. The bands consist sometimes of pyroxene or hornblende, with little or no plagioclase, or of plagioclase with small quanti-

ties of the ferro-magnesian minerals and quartz, or mainly of plagioclase and quartz, or largely of magnetite. This structure probably belongs to the time when the rock existed as an erupted material. It resembles in many respects the segregation layers to be found in some sills or bosses of eruptive materials (gabbros, dolerites, etc.) which have cooled and crystallized slowly at some considerable depth from the surface. In the second place, there is abundant evidence of mechanical deformation of the gneiss, especially along planes in certain directions. The rock has been powerfully ruptured and crushed in these lines, and has thereby acquired a granulitized and distinctly foliated structure.

Both in the massive and in the coarsely-banded gneisses abundant pegmatite veins occur, varying in width from a

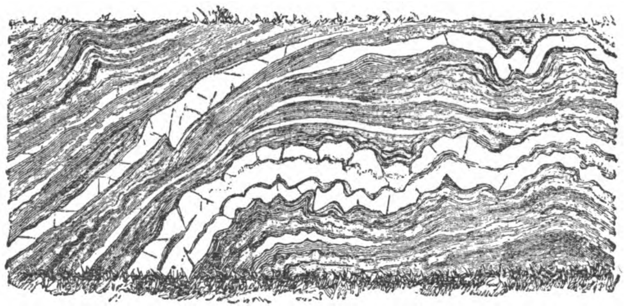

Fig. 327.—Gneiss with deformed pegmatites—Cape Wrath.

few inches to several yards, and consisting mainly of felspar and quartz. These gray veins, sometimes so numerous as to constitute a large proportion of the whole rock, occasionally inclose patches of the dark more basic rock around them, but have no determinate grouping (Fig. 326).

The pegmatites are found to have played an important part in the ultimate constitution of the gneiss. Where still quite traceable, but where they have come within the influence of mechanical deformation, they appear as rudely parallel and puckered bands (Fig. 327). But as we pass into the more thoroughly foliated portions of the gneiss, the original character of the pegmatites is found to be more and more affected, until it becomes no longer recognizable in the acquired schistose structure. The dark basic portions of the original mass pass into rudely foliated basic gneisses, and the gray pegmatites shade into the more quartzose bands asso-

now generally understood, includes the lowest series of Primary, or, as they are now called, Palæozoic deposits (see Book VI. Part II. "Palæozoic").

But it has been well established that, while in some regions the base of the Cambrian system is separated by a strong unconformability from all rocks of older date, in other tracts it can only be defined by an arbitrary line, beneath which lie other still more ancient sedimentary formations. In these primeval deposits there are records of denudation and deposition, of alternate sedimentation and terrestrial movements, of stupendous and prolonged volcanic activity, and of distinct though scanty proofs that plant and animal life had already appeared upon the face of the globe. So far as our knowledge yet goes there is no means of ascertaining the synchronism or homotaxis of these formations in widely separated regions. Fossil evidence entirely fails here as a guide, and mere mineral characters are only reliable within comparatively limited areas. All that can for the present be attempted is to determine the true order of sequence, tectonic relations and general structure of the several distinct formations in each country where they occur, without in the meantime any serious attempt at correlation.

It must further be observed that these oldest stratified rocks have very generally undergone more or less alteration during the numerous terrestrial disturbances of geological history. Lying as they do at the base of the stratified part of the earth's crust, they have shared in the movements by which, during the lapse of geological time, the fossiliferous rocks have been affected. Every intruded mass of igneous rock, every volcanic outburst, every agent of contact or of regional metamorphism had first to pass through them before

it could reach the younger rocks above. Hence not only have they usually been dislocated and plicated, but they have been abundantly invaded by intrusive materials of all ages, and their internal structure has frequently been subjected to such mechanical stresses, with accompanying chemical and mineralogical readjustments of their component materials, that they have passed into the condition of schists. In this highly altered state they often cannot be distinguished from still more ancient schists, the true origin of which is not certainly known. In some regions, indeed, where the older sedimentary formations have been greatly disturbed, a gradation may be traced from unmistakable Palæozoic or Mesozoic sediments with recognizable fossils into thoroughly crystalline and foliated schists. Sometimes this transition is doubtless due to an actual extensive metamorphism of the sedimentary rocks, and in these instances there may be no means of separating the schists of which the sedimentary origin is ascertainable from those where it is not. The whole may be Palæozoic or Mesozoic. In other cases, there seems reason to believe that the gradation is rather due to excessive plication, whereby ancient schists and Palæozoic or Mesozoic strata have been so compressed that they agree in direction of strike, and have been so folded that portions of the one series have been inclosed within the other, considerable general metamorphism having at the same time been superinduced upon the whole.

From underneath these oldest sedimentary accumulations there rises to the surface a remarkable assemblage of thoroughly crystalline rocks, which range from amorphous masses such as granite, syenite, diorite, and gabbro, through many varieties of coarse and fine foliated rocks to the most silky schists and phyllites, and which further vary in chemi-

cal composition from thoroughly acid materials (granites, felsites, etc.) to basic or even what are called "ultra-basic" compounds (peridotites, serpentines). Though sometimes amorphous over considerable spaces, and then not to be distinguished from ordinary igneous eruptive masses, they for the most part present a more or less distinctly schistose or foliated structure, some of their most abundant and conspicuous members being gneisses, often so coarsely banded as to pass into granite.

The infra-position of these crystalline rocks, combined with their prevalent stratified appearance, naturally led to their being regarded as the oldest known formation on which all the later portions of the terrestrial crust rest. But recent observations have proved many gneisses to be originally igneous rocks, sometimes even intrusive, and therefore younger in date than the rocks which they pierce (pp. 321, 1021). Where the area in which these ancient mineral masses are exposed is small, and especially where only the gneissic or schistose portion of them is seen, the oldest fossiliferous rocks may lie on them with a strong unconformability. The contrast in such conditions between the stratified conglomerates, sandstones, and shales of the Palæozoic series, and the gnarled crystalline gneisses below them is so striking as to have suggested the idea that in these gneisses we have reached the lowest and earliest part of the earth's crust. Hence arose such names as Fundamental gneiss, Urgneiss or Urgebirge.

No portion of the Geological Record has in recent years been more diligently studied than the crystalline schists, which, underlying the vast pile of fossiliferous systems, have been regarded as the earliest surviving chronicles of the history of the earth. But the problems presented by

these rocks are so many and so difficult that comparatively little progress has been made in the endeavor to group them into formations or systems comparable with those of the fossiliferous series, and to ascertain the stages of geological history of which they are the memorials. The obstacles to increase of knowledge on this subject arise from the complication and obscurity of the geotectonic relations of the rocks. We have as yet no satisfactory clew to their chronological sequence. They have undergone so many disturbances of their mass, and so many and serious alterations of their internal structure, that it is often quite impossible to be certain of their true sequence. Nothing in the least degree analogous to the evidence of fossils among the sedimentary rocks is here available. Whether eventually a determinable order of appearance among the minerals of these ancient rocks may be ascertained remains still uncertain. If it could be shown that certain minerals, or groups of minerals, came into existence at particular stages in the formation of the crystalline schists, a key might be found to some of the most difficult parts of this branch of geological inquiry. But though such a sequence has often been claimed to exist, no satisfactory proof has yet been adduced that it has been asserted on more than mere local observation. Certainly no general law of mineral sequence in geological times has hitherto been established.[1]

Thus while it is often difficult or impossible to ascertain

[1] The late T. S. Hunt was one of the main exponents of the view that the crystalline pre-Cambrian rocks were deposited as chemical sediments in a certain definite order, and that the rocks could be recognized by their mineral characters, and be thereby grouped in their proper order all over the world. See, for example, his essays on "The Taconic Question in Geology," and on "The Origin of the Crystalline Rocks" in vols. i. and ii. of the Trans. Roy. Soc. Canada. How completely this artificial system breaks down when tested by an appeal to the rocks in the field has been well shown by R. D. Irving, 7th Ann. Rep. U. S. Geol. Survey, 1888, p. 383.

the original order of succession among the crystalline schists of a particular region, it is even more difficult to form a satisfactory judgment as to the stratigraphical relations of the schists of two detached regions. There is usually no common basis of comparison between them, except similarity of mineral character and structure. But as it can be shown that even in a single area the crystalline schists may sometimes represent the results of many successive operations continuing through a long series of geological periods, it is obvious that the task of correlating these rocks in distinct, and especially in widely separated, areas must be beset with almost insuperable obstacles.

Though in many countries a complete break occurs between the lowest gneisses and the overlying Palæozoic sedimentary formations, there are other regions in which these gneisses are intimately associated with schists, limestones, quartzites, and conglomerates. The real character of this association has been variously interpreted, but on any explanation, it shows that such gneisses cannot be older than certain crystalline masses which may be regarded as probably, if not certainly, of sedimentary origin. Hence, while the inference from one series of sections has been that the gneisses belong to an early condition of the cooling crust of the globe, from another series it has been in favor of these gneisses and their associated sedimentary materials having been formed after the crust was solidified, and after mechanical and chemical sediments had begun to be accumulated.

Taking the widest view of the whole series of pre-Palæozoic rocks, with their vast piles of various sedimentary formations above, and their complex series of crystalline massive and schistose rocks below, we encounter a somewhat serious difficulty in the attempt to group the whole of this

varied assemblage of mineral masses under some common generally applicable stratigraphical name. Such a name has usually been held to imply that the rocks which it designates belong to one well-defined portion of the Geological Record. But this implication is one which every geologist who has worked among these ancient rocks would earnestly deprecate, for he has in some measure realized how vast, varied, and long-continued were the geological changes of which they are the memorials. These mutations include many transformations of the earth's surface, many disturbances of its crust, with enormous denudation and sedimentation, comparable with, if not greater than, those which in later ages were repeated again and again, even after the older fossiliferous formations were laid down. So similar have been the results that it is now difficult, or impossible, to discriminate between the more ancient and the more recent operations. To class all the crystalline schists and the great piles of sedimentary and igneous materials into which they seem to pass, by one general name, after the type of "Cambrian," "Silurian," or "Devonian," may be convenient, but in the present state of our knowledge is apt to lead to confusion, by placing together masses which may be of widely different geological ages and of wholly dissimilar origin. Various terms have been proposed for this complex assemblage of rocks, such as Primitive, Proterozoic, Azoic, Agnotozoic or Archæan. But from the data adduced in Book IV. Part VIII. regarding regional metamorphism, the student will understand how full of uncertainty must be the geological age of many areas of crystalline schists. Mere lithological characters afford no perfectly reliable test of relative antiquity. To prove that any region of crystalline schists may be "Primitive," "Azoic," or "Archæan" we

must first find these rocks overlain by the oldest fossiliferous formations. Where no evidence of this kind is available, the use of precise terms, which are meant to denote a particular geological era, is undesirable. There seems good reason to believe that the asserted "Archæan" age of many tracts of schistose and granitoid rocks rests on no better basis than mere supposition, and that, as the study of regional metamorphism is extended, the so-called "Archæan" areas will be proportionately contracted.[2]

Several distinct systems of mineral masses can be shown in some regions to exist beneath the base of the Palæozoic formations, differing so greatly in petrological characters, in tectonic relations, and probably also in mode of formation, that they cannot, without a very unnatural union, be arranged in one definite stratigraphical series. For the present it seems to me least objectionable to adopt some vague general term which nevertheless expresses the only homotaxial relation about which there can be no doubt. For this purpose the designation "Pre-Cambrian," already in use, seems suitable. The rocks which I would embrace under this epithet may include a number of separate systems or formations which have little or nothing in common, save the fact that they are all older than the base of the Cambrian rocks. Until our knowledge of these ancient masses is much more extensive and precise than it is at present, I think it would be of advantage to avoid the

[2] Dr. Barrois thus expresses himself on this subject: "A great number of the rocks considered to be Archæan in Brittany are only metamorphosed Cambrian or Silurian rocks, having merely the facies of primitive rocks. We do not think that Brittany can be the only region where this is the case; on the contrary, it seems to us probable that the Palæozoic formations are destined to spread more and more over geological maps, at the expense of the 'primitive formations,' by assuming gneissic and schistose modifications."—Ann. Soc. Geol. Nord. xi. 1884, p. 139 (ante, p. 1014 *et seq.*)

adoption of any general terminology that would involve assumptions as to their definite place and sequence in the geological record, their mode of origin, their relation to the history of plant and animal life, or their identification in different countries.

As an illustration of the danger of such assumptions, I may refer to the history of the investigation of the Laurentian rocks of Canada. From the early observations of Sir W. Logan and Mr. Alexander Murray these rocks came to be regarded as types of the oldest gneisses of the globe. They were looked upon as probably metamorphosed marine sediments that had formed the solid platform on which the whole series of fossiliferous systems of North America had been deposited. The name Laurentian applied to them was transferred to similar rock-masses in other parts of the globe, and came to be accepted as the designation of the oldest known zone in the crust of the earth. But eventually it was discovered by Mr. Lawson that some part, at least, of the Laurentian gneiss is essentially of igneous not of sedimentary origin, and is actually intrusive into what are undoubtedly sedimentary strata. It could not, therefore, itself as a whole be the oldest rock; and all the generalizations and identifications founded on its supposed position fell to the ground. The term Laurentian cannot henceforth have more than a local significance. It serves to designate certain ancient crystalline rocks of Canada, but a geologist would not now employ it to denote any of the rocks of another region, even though they might present similar general lithological characters. We must in the meanwhile be content to restrict the application of such names to the regions in which they originated. There will be much less impediment to the progress of investi-

gation by the multiplication of local names than by the attempt to force identifications for which there is no satisfactory basis. Each country will have its own terminology for pre-Cambrian formations, until some way is discovered of correlating these formations in different parts of the globe.

Although where the stratigraphical succession is most complete the gneisses that rise from under the oldest sedimentary rocks have been found to pierce these rocks, and thus to be of later date; yet in most regions no such proof of posteriority is to be seen. The coarse banded gneisses are usually the foundations on which the stratified fossiliferous formations unconformably rest. There is thus an obvious advantage in treating these gneisses first in an account of pre-Cambrian rocks. I shall here follow this arrangement, and reserve for a later section a description of the sedimentary and igneous formations which intervene between the gneisses and the base of the Cambrian system.

1. *The lowest gneisses and schists*

It has often been remarked that one of the most singular features about the oldest known crystalline rocks is the sameness of their general mineral characters in all parts of the earth. Sedimentary formations constantly vary from country to country, but when we descend beneath their lowest members we come upon a wholly different group of rocks which retain with remarkable uniformity one general type of structure and composition. These rocks include massive materials such as granite, syenite, gabbro, diorite, and hornblende-rock. But even in these a tendency to a schistose arrangement can usually be observed. By far the most generally prevalent structure is a more or less

definite foliation. In the coarse varieties it is marked by alternate bands of distinct mineral characters, orthoclase, plagioclase (commonly an acid variety), quartz, hornblende and mica (white and black) being universally conspicuous. Such rudely foliated rocks are known as coarsely-banded gneisses, and offer gradations into masses which cannot be distinguished from ordinary eruptive material. The banding is sometimes strongly marked by the separation of the more silicated from the less silicated minerals, as where layers of felspar or of quartz alternate with others of hornblende, pyroxene or biotite.

While the foliated structure and the arrangement of the minerals in parallel bands gives a bedded aspect to these rocks, the resemblance of this structure to the true bedding of detrital materials is probably more apparent than real. A little examination shows that the layers are not persistent, that they cross each other, and that portions of one may be entirely separated and inclosed within another. Whatever may have been their origin they have certainly undergone enormous mechanical compression and deformation. They have been plicated, rolled out, dislocated, and crumpled again and again. Hence, though for short distances it is possible to separate out layers or bosses of felspathic, hornblendic, pyroxenic, peridotitic, or serpentinous composition from the general body of gneiss, the geologist who tries to fix definite stratigraphical horizons by this means soon abandons the attempt in despair, and comes to the conclusion that no sequence of a trustworthy nature can be established in the body of the gneiss itself.

From the coarsest gneisses gradations may be traced to fine silky schists; and this not only on a large scale in tracts capable of being delineated on a map, but on so small

a scale as to be illustrated even in hand-specimens. Such transitions seem to arise from the different effects of mechanical deformation on materials that offered considerable differences in lithological composition and structure. Fine talcose schists, for example, can be traced to original peridotites; hornblendic and actinolitic schists to such rocks as gabbro, diorite, or dolerite.

In the older accounts of these rocks the gneisses are described as passing into or alternating with a wholly different type of rocks, among which may be included limestone (sometimes strongly graphitic), dolomite, quartzite, graphite-schist, mica-schist and other varieties of schistose material. This apparent gradation was believed to mark an original transition of the sediment out of which the gneiss was thought to have been formed into the calcareous, argillaceous, or carbonaceous sediment, which was the earliest condition of the associated limestones and schists. It was thus looked upon as evidence that the whole crystalline series represented, in a metamorphosed state, an ancient accumulation of sedimentary materials. The existence even of organic remains in the limestone was insisted upon, and the so-called *Eozoon* was cited as the most ancient relic of animal life.[3] But there is now every reason to believe such gradations to be generally deceptive. As a result of the enormous mechanical compression and deformation which these ancient rocks have undergone, igneous and aqueous materials have been so plicated and crushed together and have undergone such profound metamorphism, that it is sometimes hardly possible to trace a boundary between them. There seems no

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[3] See on this subject postea, pp. 1160, 1161, and authorities there cited.

reason to look upon the limestones, argillites, quartzites, and schists as other than intensely altered sediments, which in theory, if not in actual practice on the ground, must be separated from the gneisses.

Among the various theories which have been proposed to account for the genesis of the lowest gneisses and schists, three deserve particular mention here. (1) These rocks are by some geologists believed to be a portion of the original crust which solidified on the surface of the globe. (2) They are by others held to be ancient sedimentary rocks in a metamorphosed condition, and in some parts so changed as to have been actually melted and converted into intrusive material. (3) They are believed by yet another class of observers to be essentially eruptive rocks, and to be comparable with the deeper seated or plutonic portions of such igneous rocks as may be seen to traverse the earth's crust.

(1) From the ubiquity of their appearance, the persistence of their striking lithological characters, and especially the curious apparent blending in them of the igneous and sedimentary types of structure, the idea not unnaturally arose that the lowest crystalline rocks represent the first crust that formed on the surface of the globe.[4] These rocks have been supposed to include some of the early surfaces of consolidation of the molten globe, and some of the first sediments that were thrown down from the hot ocean which eventually condensed upon the planet. Such a speculative view of their origin may seem not incredible in regions where these ancient crystalline rocks are covered unconformably

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[4] See Credner's "Geologie," vi. *b*. Die Fundamental Formation; Erstarrungskruste. Compare also Rosenbusch, Neues Jahrb. 1889, vol. ii. p. 81.

by the oldest Palæozoic formations, from which they are marked off by so striking a contrast of structure and composition, and to which they have contributed so vast an amount of detrital material. But it must be tested by the evidence of the rocks themselves, not only where the geological record is confessedly incomplete, but where it is comparatively full. Nowhere among the lowest gneisses is any structure observable which can be compared with the superficial portion of a lava that cooled at the surface. On the contrary, the analogies they furnish are with deep-seated and slowly-cooled sills and bosses. The supposed intercalation and alternation of limestone and other presumably sedimentary materials in the old gneisses are probably all deceptive. In some regions they can be shown to be so, and it can there be demonstrated that the gneisses are really eruptive rocks which pierce the adjacent sedimentary or schistose masses, and are thus of younger age than these. If this relation can be clearly established in regions where the evidence is fullest, it is obviously safe to infer that a similar relation might be discoverable if the geological record were more complete, even in those parts of the world where the break between the lowest gneisses and the Palæozoic formations seems to be most pronounced. At least the possibility that such may be the case should put us on our guard against adopting any crude speculation about the original crust of the earth.

The present condition of these ancient rocks differs much from that which they originally possessed. In particular they have undergone enormous mechanical deformation, have been to a large extent crushed and recrystallized, and have acquired a marked schistose structure. But in every large region where they are developed we may obtain

evidence to connect them with plutonic intrusions, not with superficial consolidation, and to show that many of their essential details of structure may be paralleled among much later crystalline schists produced from the metamorphism of Palæozoic sediments and igneous rocks.

(2) That the lowest gneisses of Canada and other regions are metamorphosed sedimentary rocks was believed by probably most geologists until only a few years ago. But the increased attention which has been given to the study of the subject since Prof. Lehmann's great work on the Saxon gneisses appeared in 1884, has led to so complete a revolution of opinion that this belief, at least in its original form, is now almost wholly abandoned. Those who still hold it in a modified shape recognize that the original sediments must have differed considerably from those of any recognizably sedimentary formation, and were probably deposited under peculiar conditions. They admit that these rocks have undergone extreme metamorphism, and that the alteration of them has been carried so far as to reduce them in some places to an amorphous crystalline condition which cannot be distinguished from that of normal eruptive material. It has been maintained, indeed, that the Laurentian gneisses of Canada have been produced by the actual fusion of the older sedimentary pre-Cambrian formations and the absorption of these rocks into the general magma of eruptive material which now appears as gneiss.[5] The intrusive character of some of the gneiss, which might be regarded as proof of its really igneous origin, is accounted for by what is called an "aquo-igneous fusion" of some parts of the sedimentary rocks and their intrusion into less completely metamorphosed portions of the series.

[5] A. C. Lawson, Annual Report Canadian Geol. Surv. 1887.

(3) Probably the great majority of geologists now adopt in some form the third opinion, that the oldest or so-called "Archæan" gneisses are essentially eruptive rocks, and that they should be compared with the larger and more deeply-seated bosses of intrusive material now visible on the earth's surface. Whether they were portions of an original molten magma protruded from beneath the crust, or were produced by a re-fusion of already solidified parts of that crust or of ancient sedimentary accumulations laid down upon it, must be matter of speculation. In the gathering of actual fact we cannot go beyond their character as eruptive rocks, which is the earliest condition to which they can be traced, and we must consequently place them in the same great series as all the later eruptive materials with which geology has to deal. It is quite true that they have been profoundly modified since their original extrusion, but traces of their original character as masses of mobile, slowly crystallizing and segregating material have not been entirely effaced.

Looking at the gneisses as a whole, with their various accompaniments, we find them to form a complex assemblage of crystalline rocks which, though generally presenting a foliated structure, pass occasionally into the amorphous condition of ordinary eruptive rocks. In composition they range from granite at the one end to peridotites and serpentines at the other. Hand-specimens of these rocks in their amorphous or unfoliated condition do not differ in any essential feature from the material of ordinary intrusive bosses in later portions of the terrestrial crust, and the same similarity of structure is borne out when thin slices are placed under the microscope.

Perhaps the most convincing proof of the really eruptive nature of the gneisses is to be found in those tracts where

they have undergone least disturbance, and where therefore the way in which they traverse the adjacent rocks can be distinctly perceived. They are there seen to cross many successive zones of sedimentary material, to send out veins and protrusions, and to inclose portions of the adjacent rocks, while at the same time the surrounding masses present many of the familiar features of contact-metamorphism. Sections where these phenomena can be satisfactorily observed are no doubt comparatively rare, for in general the rocks have been so crushed and recrystallized that their original relations have been destroyed. It is in consequence of these subsequent movements that so much difficulty has been found in determining the igneous nature of the gneisses and their intrusive character with reference to the rocks adjacent to them. The abundant veins which, as in ordinary granite bosses, proceeded from the original gneiss have been compressed into long parallel bands which seem to alternate with the schists among which they were injected, while portions of the surrounding rock inclosed within the gneiss have had a foliation superinduced upon them parallel to that of these bands. Any one who first studied the older rocks where such structures are visible might easily be deceived into the belief that these alternations of parallel strips of gneiss and schist, or gneiss and limestone, really represented a continuous sequence of sedimentary material. Nor would he readily perceive his mistake until he could trace the junction-line into some tract where, by cessation of the deformation, the original relation of the two groups of rocks could be observed.[6]

It is not difficult to obtain conclusive proof that in the

[6] See A. C. Lawson, Bull. Geol. Soc. Amer. i. 1890, p. 184.

complex assemblage of rocks constituting the lowest gneiss there are not only differences of composition and structure, but also differences of relative age. Some portions of the series can be distinctly seen to have been intruded into others. True dikes can be traced among them both of acid and basic composition. In the northwest of Scotland, for example, the general body of gneiss is traversed by a multiplicity of dikes, cutting across the oldest foliation of the gneiss in a general northwesterly direction. A detailed study of such an area reveals the fact that the fundamental rocks represent a prolonged series of igneous protrusions. As this complicated mass of eruptive material has subsequently undergone profound alteration by dynamo-metamorphism, the difficulties in unravelling its history need cause no surprise.

Leaving out of account the dikes which undoubtedly mark later injections of igneous material, and confining our attention to the general mass of gneiss in its variations from an amorphous or granitoid condition through the coarse banded varieties to the finer schistose types, we may pursue the history of these puzzling rocks by comparing them with the larger intrusive bosses and sills that have accompanied the volcanic eruptions of all geological periods. In these deep-seated and slowly cooled masses of igneous material, as has already been pointed out (p. 962), we may frequently observe evidence of the segregation of the component minerals in bands or irregular patches. Such a segregation seems to have taken place sometimes after the erupted rock had come to rest, sometimes while it was still in movement. In the latter case the layers of separated materials may sometimes have been dragged forward so as to acquire a somewhat banded or streaky structure. How far

the characteristic arrangements of the minerals in the coarse banded gneisses may have arisen from a process of this kind in the consolidation of originally eruptive materials, remains still an open question, though the progress of research favors the idea that such has really been to a large extent their source.[7]

It is certain, however, that, besides the original banded and probably segregated structure, the gneisses, as the result of much mechanical deformation, have had other and later structures superinduced upon them, sometimes at successive periods of disturbance. The most massive granitoid rocks have thus been crushed down under great strain, and have recrystallized as fine granulitic gneiss or mica-schist. Epidiorites and amphibolites have by a similar process been converted into hornblende-schists. In these cases the reconstructed rocks usually exhibit a finely schistose structure, quite distinct from that of the parent mass, but with no markedly banded arrangement. Occasionally, however, in the recrystallization of the materials, segregation into more or less definite layers or centres has come into play, so that in this obviously secondary arrangement a certain resemblance may be traced, though on a small scale, to the much coarser bands in the earliest remaining condition of the oldest gneisses.

There is yet another source of difficulty in judging of the relative age and origin of various structures among the crys-

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[7] This inference applies more particularly to the coarsely banded gneisses where the individual layers, consisting in great part of different minerals, resemble some of the segregation bands in eruptive masses (p. 1021). There can be little doubt that, as already remarked, the efficacy of mechanical deformation as a factor in the production of gneisses has been pushed too far. It will account for the crushed granulitic and schistose condition, but hardly for the coarsely banded structure, where the layers consist of very different mineral aggregates.

talline schists. As has already been pointed out (p. 1002), it is now well established that granite, besides breaking through the old rocks and forming huge bosses, as well as abundant veins among them, has sometimes been introduced into their substance in such a way that they seem to be permeated by the granitic material. Minute layers and lenticles of this material, quite uncrushed, may be traced between the foliation planes of granulitic gneisses and different schists. But where subsequent movement has crushed and drawn out these intercalated layers, younger gneiss is produced that simulates with extraordinary closeness some aspects of the most ancient and, so to say, original gneisses.[8] This transformation appears to take place even among schists that can be shown to have been originally sedimentary rocks. So that by a new pathway of inquiry we are brought once more to the old doctrine of the cycle of change through which the materials of the earth's crust pass. The most ancient gneisses exposed to disintegration on the earth's surface have furnished materials for the formation of sedimentary deposits, which, after being deeply buried within the earth's crust, crushed, plicated, and permeated with granitic material, present once more the aspect of the old gneisses from which they were in the first instance derived.

It is only when the complex tectonic relations of the several masses composing the oldest crystalline rocks are closely studied that we can adequately realize how hopeless would be the attempt to establish anything of the nature of a stratigraphical sequence among them. Where different eruptive materials present proofs of successive intrusion, we

[8] See observations of J. Horne in "Geological Survey Report," Report of the Science and Art Department for 1892.

have indeed a clew to their relative age; but such evidence carries us but a small way. The gneisses where obviously intrusive are indisputably of eruptive origin, but they alternate with finely schistose bands which sometimes seem to cut them. The bedding or banding of the rocks affords no guide whatever as to sequence. It has been so folded and crumpled that even if it represented original stratification it could probably never be unravelled. But there is every reason to believe that it bears no real analogy to stratification. It may sometimes represent, as already stated, layers of segregation and flow-structure in an original igneous magma, at other times planes of movement in the crushing of already consolidated material. But whatever may have been its origin, it remains now in an inextricable complexity. Here and there, indeed, for short distances some well-marked band of rock may be traced, but the various rock-masses generally succeed each other in so rapid and tumultuous a manner as to defy the efforts of the field-geologist who would patiently map them.

As a rule, only where the earliest type of gneiss has been invaded by subsequently intruded masses can a successful attempt be made to disentangle the confused structure. Successive systems of dikes may thus be traced, and evidence may be obtained that powerful dynamic stresses affected the rocks between some of these intrusions. The dikes have sometimes been crushed, plicated, and disrupted until they have been reduced to isolated patches of schist irregularly distributed among the reconstructed gneiss. And through these involved and complicated masses newer groups of dikes have risen, to be again subjected to mechanical deformation.

The question may occur to the student whether this com-

plex system of evidently plutonic igneous rocks was ever connected with any superficial volcanic activity. No such connection has yet been definitely ascertained, but it may be regarded as highly probable. If the most ancient gneisses with their dikes and bosses were the deep-seated portions of the successive uprisings of the igneous magma which culminated in volcanic eruptions, we may hope eventually to discover some trace of the materials that were thrown out to the surface and accumulated there. In some of the overlying pre-Cambrian masses of sedimentary rocks abundant lavas, tuffs, and agglomerates have been found, indicating the outpouring of volcanic material at the surface during the deposition of these sediments. The vast scale of these volcanic eruptions may be inferred from the fact that in the Lake Superior region the accumulated materials discharged at the surface attained a thickness which has been estimated at more than six and a half miles. It may be eventually discovered that some of these superficial manifestations of volcanic action have been connected with bosses, sills, or dikes that form part of the body of the gneiss below.

It must be confessed that much detailed work among the lower gneisses in all parts of the world is needed before the many problems which they present are solved. But the following conclusions regarding them may now be regarded as certain:—these rocks are in the main various forms of original eruptive material, ranging from highly acid to highly basic; they form in general a complex mass belonging to successive periods of extrusion; some of their coarse structures are probably due to a process of segregation in still fluid or mobile, probably molten, material consolidating below the surface; their granulitized and schistose characters, and their folded and crumpled structures point to subsequent

intense crushing and deformation; their apparent alternations with limestone and other rocks, which are probably of sedimentary origin, are deceptive, indicating no real continuity of formation, but pointing to the intrusive nature of the gneiss.

2. *Pre-Cambrian sedimentary and volcanic groups*

In different parts of the world enormous masses of rock are now known to intervene between the oldest or "Archæan" gneisses, and the bottom of the fossiliferous series of formations. It was in Canada that these rocks were first studied. Logan and Murray grouped them under the general name of Huronian, and they were believed to fill up the gap between the Laurentian gneiss on the one hand, and the Potsdam sandstone or base of the fossiliferous series on the other. Later more detailed study of these rocks in Canada and the adjoining regions of the United States has shown them to possess even a greater importance than their original discoverers imagined, for they have been found to consist of several distinct groups or systems, attaining a vast thickness and presenting a record of stupendous disturbances, denudations and depositions of sediment, together with memorials of extensive and prolonged volcanic action. In the higher members of these sedimentary deposits, distinct remains of animal life have in several regions been found. There is thus opened out the possibility of the ultimate discovery of a series of fossiliferous formations even below the base of the Palæozoic series.

Where metamorphism has not interfered with the recognition of their original characters, these ancient sedimentary rocks present no structural feature to distinguish them from the detrital accumulations of higher parts of the geological

record. They consist of clays and muds hardened into shales and slates, of sands compacted into sandstones and quartzites, of gravels and shingles solidified into conglomerates. These rocks prove beyond question that the processes of denudation and deposition were already in full operation with results exactly comparable to those of Palæozoic and later time.

Few parts of the stratified crust of the earth present greater interest than these earliest remaining sediments. As the geologist lingers among them, fascinated by their antiquity and by the stubbornness with which they have shrouded their secrets from his anxious scrutiny, he can sometimes scarcely believe that they belong to so remote a part of the earth's history as they can be assuredly proved to do. The shales are often not more venerable in appearance than those of Cambrian or Silurian time, and show as clearly as these do their alternations of finer and coarser sediment. The sandstones display their false-bedding as distinctly as any younger rock, and one can make out the shifting character of the currents and the prevalent direction from which they brought the sand. The conglomerates in their well-rounded fragments tell as distinctly as the shingle of a modern beach of the waste of a land-surface and the pounding action of waves along a shore.

Not only are these structural details precisely similar to those of younger detrital rocks, but we may here and there detect the remains of the pre-Cambrian topography from which these primeval sediments were derived, and on which they were deposited. Hills and valleys, lines of cliff and crag, rocky slopes and undulating hollows have been revealed by the slow denudation of the pre-Cambrian strata under which these features were gradually buried. To this

day so marvellously has this early land-surface been preserved under its mantle of sediment during the long course of geological time, that even yet we may trace its successive shore-lines as it gradually settled down beneath the waters in which its detritus gathered. We may follow its promontories and bays and mark how one by one they were finally submerged and entombed beneath their own waste.[9]

But these ancient stratified formations do not consist merely of clastic sediments. They include important masses of limestone and dolomite, sometimes highly crystalline, but elsewhere assuming much of the aspect of ordinary gray compact Palæozoic limestone. Sometimes they contain a considerable amount of graphite, and some of the shales are highly carbonaceous. In other places they are banded with layers and seams or nodules of chert, in a manner closely similar to that in which the Carboniferous Limestone of Western Europe contains its siliceous material. Sometimes the chert bands are as much as forty-five feet thick. The general character of these mingled carbonaceous, calcareous and siliceous masses at once reminds the observer of rocks which have undoubtedly been formed by the agency of organic life. Moreover there occur extensive deposits of iron-carbonate associated like the limestone with chert, and again recalling the results of the co-operation of plant and animal life. The large amount of carbon in some of the shales points likewise in the same direction.

It must be confessed, however, that actual traces of recognizable organic forms have only been found in a few places. Various more or less determinable patelloid or

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[9] These features are admirably displayed in Ross-shire, N.W. Scotland, where the Lewisian gneiss, carved into hills and valleys, has been buried under the Torridon Sandstone (postea, p. 1177).

discinoid shells, fragments of what appear to have been trilobites (like *Olenellus*, *Olenoides* or *Paradoxides*), small and rather obscure forms like *Hyolithes*, and others like *Stromatopora*, indicate a low fauna somewhat like that of the Cambrian system above.[10] Most of these fossils have been detected by Mr. Walcott below the *Olenellus* zone or base of the Cambrian rocks in the Grand Cañon of the Colorado. In the Animikie district of Lake Superior, fossil tracks and shells like *Lingula*, and some obscure forms like trilobites, have also been met with. More recently Dr. Barrois has traced a band of graphitic quartzite for a long way in the gneiss of Brittany, and has detected in it the presence of radiolarians, belonging to their most primitive group, the Monosphæridæ.[11]

Reference may be made here to the controversy regarding the true nature of certain curious aggregates of calcite and serpentine, which were found many years ago in some of the limestones associated with the lower or Laurentian gneisses of Canada. These minerals were found to be arranged in alternate layers, the calcite forming the main framework of the substance, with the serpentine (sometimes loganite, pyroxene, etc.) disposed in thin, wavy, inconstant layers, as if filling up flattened cavities in the calcareous mass. So different from any ordinary mineral segregation with which he was acquainted did this arrangement appear to Logan, that he was led to regard the substance as probably of organic origin.[12] This opinion was adopted and the structure of the supposed fossil was worked out in detail

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[10] C. D. Walcott, 10th Ann. Rep. U. S. Geol. Surv. 1890, p. 552.

[11] Compt. Rend. 8th August, 1892.

[12] Rep. Geol. Surv. Canada, 1858. Amer. Journ. Sci. xxxvii. 1864, p. 272. Q. J. Geol. Soc. xxi. 1865. p. 45. Harrington's "Life of Sir W. E. Logan," 1883, pp. 365–378.

by Sir J. W. Dawson of Montreal,[13] who pronounced the organism to be the remains of a massive foraminifer which he called *Eozoon*, and which he believed must have grown in large thick sheets over the sea-bottom. This view was likewise adopted by the late Dr. W. B. Carpenter,[14] who, from additional and better specimens, described a system of internal canals having the characters of those in true foraminiferal structures. Other observers, however, notably Professors King and Rowney of Galway,[15] maintained that the "canal-system" is not of organic but of mineral origin, having arisen in many cases "from the wasting action of carbonated solutions on clotules of 'flocculite,' or, it may be, saponite—a disintegrated variety of serpentine, and in others from a similar action on crystalloids of malacolite. In both cases," according to Prof. King, "there are produced residual 'figures of corrosion' or arborescent configurations, having often a regular disposition." The regularity of these forms is attributed by Messrs. King and Rowney to their having been determined by a mineral cleavage.[16] Prof. Möbius of Kiel[17] also opposed the organic nature of *Eozoon*, maintaining that the supposed canals and passages are merely infiltration veinings of serpentine in the calcite. In some cases, however, the "canal-system" is not filled

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[13] Q. J. Geol. Soc. xxi. 1865, p. 51; xxiii. 1867, p. 257. See also his "Acadian Geology," 2d edit., "Dawn of Life," 1875, and "Notes on Specimens of Eozoon Canadense," Montreal, 1888.

[14] Proc. Roy. Soc. 1864, p. 545. Q. J. Geol. Soc. xxi. 1865, p. 59; xxii. 1866, p. 219.

[15] Quart. Journ. Geol. Soc. xxii. 1866, p. 185.

[16] Prof. W. King, Geol. Mag. 1883, p. 47. See the views of these writers, summarized in their work, "An old Chapter in the Geological Record with a new Interpretation," London, 1881, where a full bibliography will be found.

[17] "Palæontographica," xxv. p. 175; Nature, xx. p. 272. See replies by Carpenter and Dawson, Nature, xx. p. 328. Amer. Journ. Sci. (3) xvii. p. 196; also Amer. Journ. Sci. (3) xviii. p. 117. See also A. G. Nathorst, Neues Jahrb. 1892, i. p. 169.

with serpentine but with dolomite, which seems to prove that the cavities must have existed before either dolomite or serpentine was introduced into the substance. It may be admitted that no structure precisely similar to that of some of the specimens of *Eozoon* has yet been discovered in the mineral kingdom.[18] But it must also be conceded that the chances against the occurrence of any organism in rocks of such antiquity, and which have been so disturbed and mineralized, are so great that nothing but the clearest evidence of a structure which cannot be other than organic should be admitted in proof. If any mineral structure could be appealed to, as so approximately similar as to make it possible that even the most characteristic forms of *Eozoon* might be due to some kind of mineral growth, the question would be most logically settled in a sense adverse to the organic nature of the substance.[19]

The opinion of the organic nature of *Eozoon* has been supposed to receive support from the large quantity of graphite found throughout the older rocks of Canada and the northern parts of the United States. This mineral

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[18] The nearest resemblance to the "canal-system" of Eozoon which I have seen in any undoubtedly mere mineral aggregate is in the structure known as micropegmatite, where, in the intergrowth of quartz and orthoclase, arborescent divergent tube-like ramifications of the one mineral are inclosed within the other (see Fig. 5). Mr. Rudler, who called my attention to the resemblance, showed me a remarkable micropegmatite, brought from the Desert of Sinai by Prof. Hull, in which the Eozoonal arrangement is at once suggested.

[19] Whitney and Wadsworth in their "Azoic System" (Bull. Mus. Comp. Zool. Harvard, 1884, pp. 528–548) give a summary of the controversy, and decide against the organic origin of Eozoon. From the zoological side also Rœmer and Zittel decline to receive Eozoon as an organism. In the pre-Cambrian rocks of Bohemia and Bavaria specimens were some years ago obtained showing a structure like that of the Canadian Eozoon. They were accordingly described as of organic origin, under the respective names of Eozoon bohemicum and E. bavaricum. But their true mineral nature appears to be now generally admitted. The original "Tudor specimen" of Eozoon figured by Dawson has recently been re-examined by Mr. J. W. Gregory, who decides against its organic origin. Quart. Journ. Geol. Soc. xlvii. 1891, p. 348.

occurs partly in veins, but chiefly disseminated in scales and laminæ in the limestones and as independent layers. Sir J. W. Dawson estimates the aggregate thickness of it in one band of limestone in the Ottawa district as not less than from 20 to 30 feet, and he thinks it is hardly an exaggeration to say that there is as much carbon in the "Laurentian" as in equivalent areas of the Carboniferous system. He compares some of the pure bands of graphite to beds of coal, and maintains that no other source for their origin can be imagined than the decomposition of carbon-dioxide by living plants.[20]

An important and interesting feature of the pre-Cambrian rocks is the occurrence among them of abundant proofs of extensive and long-continued volcanic action. Sheets of lava having an aggregate thickness of many thousand feet are interstratified with coarse and thick volcanic conglomerates and tuffs. The eruptive rocks include both basic and acid varieties, for among them are found diabases, melaphyres (often highly amygdaloidal), porphyrite, gabbro, quartzless and quartziferous porphyry, rhyolitic felsite, augite-syenite, and granite. Some further details regarding these masses will be given in subsequent pages. In the Lake Superior region the amygdaloidal diabases and the conglomerates are largely impregnated with native copper.

While in some regions the original characters of pre-Cambrian rocks, sedimentary and eruptive, are as easily determinable as those of any ordinary Palæozoic series, in others they have been more or less effaced by subsequent

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[20] But compare the advocacy of an opposite opinion by Whitney and Wadsworth, "Azoic System," p. 539.

geological revolutions. Gradations can sometimes be traced, as in the Penokee district of Wisconsin, from graywackes and slates through every stage of increasing metamorphism into mica-schists which present every appearance of complete original crystallization.[22] The limestones have passed into the condition of marbles; the iron ores, probably originally carbonates, have become oxidized into limonite, hæmatite and magnetite, while the ore has been concentrated into separate masses. The "greenstones" have passed into the condition of true schists.[23] Some of these metamorphosed areas present so many points of resemblance to the lower gneisses already described that it is not at all surprising that they should have been confounded, and that their true relations should only have been made out after much controversy and long-continued detailed study.

A great deal of discussion has arisen as to the true relations of these pre-Cambrian stratified and eruptive rocks to the coarse-crystalline banded gneisses above described. In some sections a complete and strong unconformability occurs between the two series, and no doubt can there exist as to the enormous break that separates them. In other regions, however, the lower gneisses are so involved with schists, limestones, and conglomerates that no satisfactory separation of them has been made, while in some places the gneiss actually crosses these rocks intrusively. Each country or district may present its own phase of the problem. At present we have no means of determining the true correlation of the pre-Cambrian rocks in separate and especially in distant areas. If we admit that the lowest

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[22] G. H. Williams, Bull. U. S. Geol. Surv. No. 62, 1890.
[21] R. D. Irving and C. R. Van Hose, 10th Ann. Rep. U. S. Geol. Surv. 1890, p. 434.

gneisses with their accompaniments form an eruptive assemblage of which the component portions may belong to widely different periods of time, it is quite conceivable that a certain group of sedimentary formations may be found in one district to lie unconformably on these gneisses, and in another to be pierced by some of their younger members.

There is likewise some difficulty in fixing the upper limit of the pre-Cambrian formations. Where the Cambrian rocks lie on them unconformably the obvious stratigraphical break forms a convenient line of division. But in some countries a thick mass of conformable sedimentary rocks underlies the *Olenellus*-zone which has been taken as the base of the Cambrian system, and in these instances the line of separation becomes entirely arbitrary. Sections of this nature are of great value, inasmuch as they impress upon the geologist that the artificial character of the divisions by which he classes the geological record is not confined to the fossiliferous formations, but marks also those of the pre-Cambrian series. Unconformabilities, even where widespread, cannot be regarded as universal phenomena, and though of infinite service in classification, should be employed with the full consciousness that the blanks which they represent do not indicate any world-wide interruption of geological continuity, but may at any moment be filled up by the evidence of more complete sections.

With regard to the comparative value of the pre-Cambrian rocks in the chronology of geological history no precise statement can be made. But various circumstances show that they must represent an enormous period of time. We shall see in succeeding pages that from the general character of the Cambrian fauna it must be regarded as certain that life had existed on the earth for a long series

of ages before that fauna appeared, in order that such well-advanced grades of organization should then have been reached. One of the most interesting chapters of geological history would be supplied if some adequate account could be given of the stages of this long pre-Cambrian evolution.

But the mere thickness and variety of the pre-Cambrian formations, together with their unconformabilities and other structural features, suffice to prove that they represent an enormous chronological interval. In North America, where, so far as at present known, they are most extensively developed, they are estimated to attain a thickness of more than 65,000 feet, or upward of twelve miles, and have been regarded there as chronologically quite equal to the whole of the rest of the geological record. Even when we eliminate the bedded volcanic rocks from the computation and reduce the remaining sedimentary series to the lowest allowable dimensions, an enormous mass of stratified material remains, which, even if it had been uninterruptedly deposited, would have required a period of time comparable to probably more than that taken by the whole of the Palæozoic systems. But we know that the deposition was not continuous. Both in North America and in Europe there is clear evidence from marked unconformabilities that it was broken by epochs of upheaval and by long periods of extensive denudation. It is evident, therefore, that we must assign to the records of pre-Cambrian time a far more important chronological value than has generally been apportioned to them.

If, as already stated, it is impossible in the present state of science to find any satisfactory basis for the correlation of the oldest gneisses in distant and disconnected regions, it is not more practicable to establish a basis of correlation

for the pre-Cambrian stratified formations. The evidence of fossils hardly as yet exists, and mere lithological characters are in such circumstances of little value. All that can be done at present is to work out the succession of rocks in each well-defined geographical and geological area, giving local names to the stratigraphical groups or systems that may be established, and trusting to future research for some method of possibly ascertaining the parallelism of these divisions in different parts of the world. Hence in the following summary of the characters of the pre-Cambrian rocks in the Old World and in the New no attempt will be made to adopt any general terminology, but in each country the names and divisions adopted there will be given.

§ ii. Local Development

Britain.—Much attention has been given in recent years to the pre-Cambrian rocks of the British Isles and a voluminous literature has arisen concerning them. Rocks, however, have been claimed as pre-Cambrian which are certainly eruptive masses of later date than parts of the Lower Silurian series. Others have been assigned to a similar position, though their relations to the older Palæozoic rocks cannot be seen; while others again cannot properly be disjoined from the lower portion of the Cambrian system. In the confusion which has thus been introduced it will be most satisfactory to restrict attention to those rocks and areas about the true relations of which there appears to be least room for dispute.

In no part of the European area are rocks of pre-Cambrian age more admirably displayed than in the northwest of Scotland. Their position there, previously indicated by Macculloch[23] and Hay Cunningham,[24] was first definitely

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[23] "A Description of the Western Islands of Scotland," 1819.

[24] "Geognostical Account of the County of Sutherland," Highland Soc. Trans. viii. 1841, p. 73.

established by Murchison,[25] who, with Nicol as his earlier colleague, showed that an ancient gneiss is unconformably overlain with a thick mass of dull red sandstones above which lie (also unconformably, as was eventually discovered) quartzites and limestones containing fossils which he referred to the Lower Silurian system. He regarded the red sandstones as probably Cambrian, and after proposing the terms Fundamental and Lewisian for this underlying gneiss, he finally adopted instead of them the term Laurentian, believing that the rocks so designated by him in this country were equivalents of those which had been studied and described by his friend Logan in Canada.[26] More recently the officers of the Geological Survey have discovered the *Olenellus*-zone in strata intermediate between the quartzites and the limestones.[27] These formations are thus shown to be of Cambrian age. The base of the Cambrian series in the northwest of Scotland lies at the bottom of the quartzite which reposes with a strong unconformability, sometimes on the red sandstones, sometimes on the gneiss. Hence these last two distinct groups of rock are now definitely proved to be pre-Cambrian. As they differ so strongly from each other their respective limits can be easily followed, and as they extend over a united area of hundreds of square miles in the northwest of Scotland they afford abundant opportunities for the most detailed examination. The rocks of this region may be arranged in descending order as in the table on the following page:

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[25] Brit. Assoc. 1885, Sect. p. 85; 1857, Sect. p. 82; 1858, Sect. p. 94; Quart. Journ. Geol. Soc. xiv. 1858, p. 501; xv. 1859, p. 353; xvi. 1860, p. 215; xvii. 1861, p. 171. Nicol, Quart. Journ. Geol. Soc. xiii. 1857, p. 17; xvii. 1861, p. 85; Brit. Assoc. 1858, Sect. p. 96; 1859, Sect. p. 119.

[26] In the elucidation of the true relations of the rocks to each other in the N.W. of Scotland later geologists have taken part, more especially Dr. Hicks, Prof. Bonney, Mr. Hudleston, Dr. Callaway, and above all, Prof. Lapworth and the officers of the Geological Survey. The literature of the subject, up to 1888, will be found condensed in the Report by the Geological Survey, in Quart. Journ. Geol. Soc. vol. xliv. 1888, p. 378. The more important announcements since that date will be referred to in the sequel.

[27] Brit. Assoc. 1891, Sect. p. 633. Peach and Horne, Quart. Journ. Geol. Soc. xlviii. 1892, p. 227.

Cambrian.		Limestones of Durness with numerous fossils indicating Cambrian and possibly lowest Silurian horizons. Serpulite grit and "Fucoid beds," with *Salterella* and *Olenellus* = Olenellus zone. Quartzites with abundant worm-burrows.
		[Unconformability.]
Pre-Cambrian.	Torridonian.	Dull red sandstones, shales and conglomerates attaining a thickness of at least 8000 or 10,000 feet, the upper limit being lost by denudation and unconformability.
		[Strong unconformability.]
	Lewisian.	Coarse gneisses and schists derived from a complex aggregate of eruptive rocks of different ages by mechanical deformation. In one area there appears to be a group of still more ancient and sedimentary rocks through which the gneisses have been intruded.

LEWISIAN.—The oldest gneisses of Scotland form the Isle of Lewis with the rest of the Outer Hebrides, and extend in an interrupted band on the mainland from Cape Wrath at least as far as Loch Duich. For this important and well-defined group of rocks the name Lewisian, formerly proposed by Murchison, seems most appropriate. As originally studied, it was thought to be a comparatively simple formation. Its foliation-planes, like those of other similar rocks, were supposed to mark layers of deposit, and to show that the rocks were metamorphosed sediments. It was believed to have been thrown into sharp anticlinal and synclinal folds, of which the axes ran in a general north-westerly direction. The detailed mapping of the region by the Geological Survey, however, has shown that the apparent bedding is wholly deceptive, and that the seeming simplicity gives place to an extraordinarily complex structure. Instead of being altered sediments, the rocks have been ascertained to consist essentially of eruptive masses, varying from an extremely basic to a markedly acid type, and belonging to successive periods of extrusion.[28]

As a whole the gneiss is considerably more basic than the typical rocks to which this term was originally given. It commonly consists of plagioclase felspar with pyroxene,

[28] For details regarding the gneiss of N.W. Scotland and the remarkable geological structure of that region see the report of the Geological Survey, Quart. Journ. Geol. Soc. xliv. 1888, p. 378, where the work of Messrs. Peach, Horne, Gunn, Clough, Hinxman and Cadell is summarized.

hornblende, and magnetite, sometimes with blue opalescent quartz, and sometimes with black mica. These predominant minerals are sometimes distributed quite without structure, so that the rock appears as a syenite, diorite, gabbro, peridotite, picrite, pyroxene-granulite, or other massive amorphous member of the eruptive rocks. From these structureless areas, which probably represent most nearly the original condition of the materials, gradations can be traced into well foliated masses, and into coarsely banded gneisses, where the minerals have segregated into lenticular bands and elliptical or irregular concretions. Though it

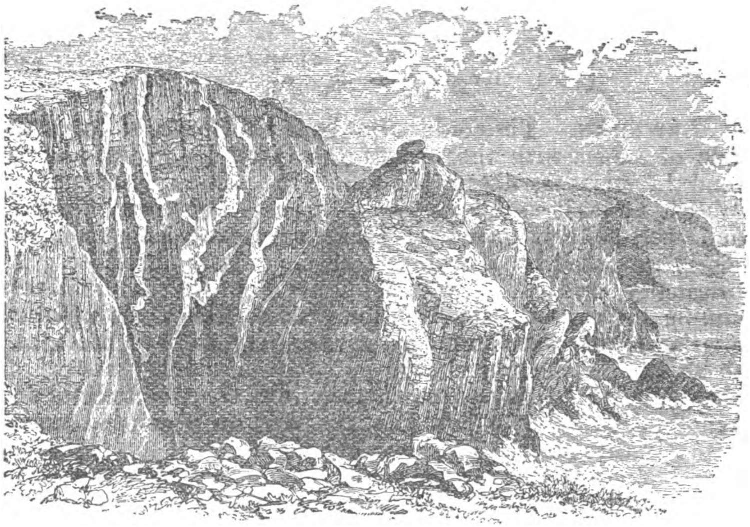

Fig. 326.—Veins of pegmatite in gneiss, south of Cape Wrath.

may often be difficult in practice to distinguish types of structure among these rocks, two such types may in many instances be recognized. In the first place, there is the banded or segregated structure, in which the predominant minerals have separated out from each other, and have crystallized more or less apart, often in coarse aggregations, forming in this way distinct bands or folia which, since they are often crossed by the planes of foliation, are evidently older than the development of these planes. The bands consist sometimes of pyroxene or hornblende, with little or no plagioclase, or of plagioclase with small quanti-

ties of the ferro-magnesian minerals and quartz, or mainly of plagioclase and quartz, or largely of magnetite. This structure probably belongs to the time when the rock existed as an erupted material. It resembles in many respects the segregation layers to be found in some sills or bosses of eruptive materials (gabbros, dolerites, etc.) which have cooled and crystallized slowly at some considerable depth from the surface. In the second place, there is abundant evidence of mechanical deformation of the gneiss, especially along planes in certain directions. The rock has been powerfully ruptured and crushed in these lines, and has thereby acquired a granulitized and distinctly foliated structure.

Both in the massive and in the coarsely-banded gneisses abundant pegmatite veins occur, varying in width from a

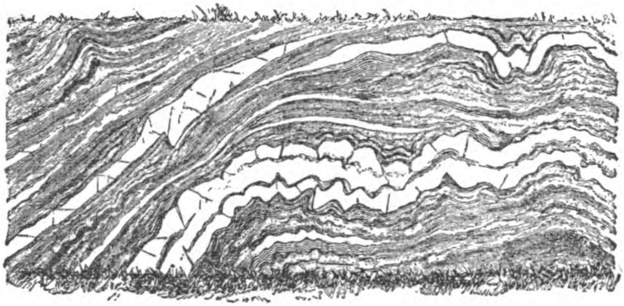

Fig. 327.—Gneiss with deformed pegmatites—Cape Wrath.

few inches to several yards, and consisting mainly of felspar and quartz. These gray veins, sometimes so numerous as to constitute a large proportion of the whole rock, occasionally inclose patches of the dark more basic rock around them, but have no determinate grouping (Fig. 326).

The pegmatites are found to have played an important part in the ultimate constitution of the gneiss. Where still quite traceable, but where they have come within the influence of mechanical deformation, they appear as rudely parallel and puckered bands (Fig. 327). But as we pass into the more thoroughly foliated portions of the gneiss, the original character of the pegmatites is found to be more and more affected, until it becomes no longer recognizable in the acquired schistose structure. The dark basic portions of the original mass pass into rudely foliated basic gneisses, and the gray pegmatites shade into the more quartzose bands asso-

ciated with them. Thus the derivation of the gneisses from amorphous igneous rocks may be regarded as established beyond dispute.

As illustrative of the conclusion that, while there seems good reason to believe that the segregated or coarsely-banded structure indicates a separation and crystallization of materials out of a still unconsolidated igneous magma, the predominant foliation structures which traverse these bands were produced by powerful mechanical movements, such a section as that represented in Fig. 328 may be cited. The mineral bands have there been violently plicated, and have been cut through by a succession of thrust-planes (*t t*), by which they have been pushed forward and piled over

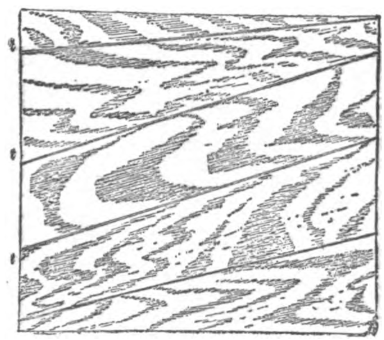

Fig. 328.[29]—Section of Lewisian gneiss, embracing a vertical surface of several hundred square yards.

each other. The foliation thus superinduced follows the direction of movement, and crosses indiscriminately the boundaries of the different aggregates of original materials. Viewed from a little distance the darker and lighter crumpled layers form a striking feature on many coast cliffs, but they are seen to be abruptly truncated above and below by thrust-planes parallel to which the gneiss has sometimes been crushed and rolled out into flaggy sheets (Fig. 329). These ancient structures are similar to those so abundantly developed in the younger or eastern gneisses already (p. 1037) referred to. They seem to make it certain that after the consolidation of the complex assemblage of igneous rocks

[29] Figs. 328, 331, 334 are taken by permission of the Council of the Geological Society from the Report of the Geological Survey published in the Quarterly Journal of the Society for August, 1888.

and the production of their pegmatites, a series of powerful mechanical movements crumpled, crushed, and sheared the whole mass, and produced in it a distinct foliation. Portions of one kind of material, such as dark hornblende, have been separated from the rest, and have been involved as distinct lumps in another variety such as gray quartzose gneiss.

The detailed investigations of the Geological Survey have further shown that, after the first foliation had been superinduced, a new series of igneous protrusions invaded the gneisses, chiefly in the form of dikes. The earliest and most conspicuous of these are extraordinarily abundant basalt-rocks, running as long parallel bands in a general W.N.W. and E.S.E. direction. The latest are dikes of granite or syenite, while probably of intermediate date are

Fig. 329.—Plicated banded gneiss between masses that have been sheared parallel to the thrust-planes, north side of Loch Torridon.

certain highly basic dikes, among which peridotite and picrite are characteristic. The evidence as to the relative dates of these igneous intrusions being tolerably clear, we have here proofs of a long interval of subterranean activity, during which the magma that was first injected into the gneiss in such basic form as basalt parted progressively with its more basic constituents until it became in the end quite acid. It is interesting to find, even among the most ancient rocks of Britain, a sequence of eruptive materials, like that which appears so markedly among the Palæozoic and Tertiary volcanic phenomena (p. 444).

After the injection of these various eruptive materials, the whole region of the northwest of Scotland was once more subjected to powerful dynamic movements, whereby all the rocks were profoundly affected. The results of these opera-

tions are found partly in vertical lines or bands of rupture or crushing, along which, sometimes for a breadth of 500 feet or more, the rocks have been crushed or sheared, partly in thrust-planes which are often nearly flat. In some instances the intrusive dikes remain quite distinct, but have acquired a more or less distinct foliated structure, the planes of foliation being parallel to those which traverse the surrounding gneiss (Fig. 330). But the alterations produced by these enormous terrestrial stresses are most strikingly displayed by some of the more basic dikes.

Along the central portions of one of the basalt or dolerite dikes, the massive rock may be observed to have been broken into oblong lenticles round which the more crushed material passes into hornblende-schist, while the outer por-

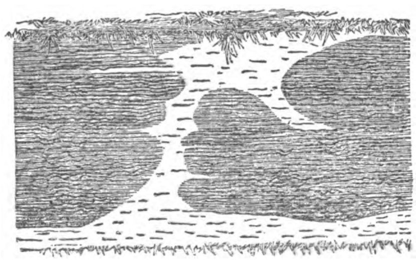

Fig. 330.—Foliation induced in a granite vein in gneiss, Loch Laxford.

tions of the dike likewise become entirely schistose (Fig. 332). So great has been the metamorphism that the augite for the most part has been changed into hornblende. The felspars have assumed an opaque granular condition, and the rock becomes a diorite. The peridotite and picrite dikes have been converted into soft talcose schists, the veins and belts of granite into granitoid gneiss. Such, too, has been the compression that in some cases dikes of 50 or 60 yards in breadth are reduced, where one of these crush-lines crosses them obliquely, to a thickness of no more than four feet, while the horizontal displacement sometimes amounts to a quarter of a mile (Fig. 331). Besides foliation produced parallel to the vertical or highly inclined lines of movement, a similar structure has been superinduced in the gneiss parallel to the gently inclined thrust-planes.

The influence of these movements, not only on the amorphous dikes and veins, but on the general body of the already foliated gneiss itself, has been profound.

Where the change has been most complete a new foliation has completely obliterated the original structure. From this extreme every gradation may be traced back to the first schistose structure, and thence into the original amorphous condition. In many cases this new foliation has been produced nearly or quite along the planes of the old structure. But everywhere examples may be observed where (as in Fig. 333) the alternate bands of lighter and darker material are traversed obliquely by the newer structure, which may be perfect in the dark more basic bands and hardly developed in the gray more quartzose parts.

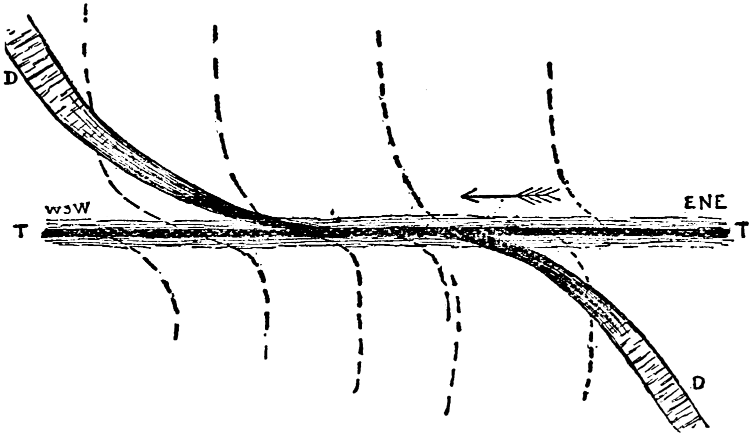

Fig. 331.—Ground-plan showing deflection and disruption of dikes in the Lewisian gneiss of N.W. Scotland.

TT, Thrust-plane, DD, Dike, deflected about one-quarter mile and much compressed. The dotted lines show the strike of the gneiss and its displacement by the thrust-plane; the fine parallel lines in the dike and in the gneiss mark the direction of the newer schistosity developed by the thrust-movement, which was in the direction of the arrow.

It is obvious that the various terrestrial movements indicated by the complex composition and structure of the Lewisian gneiss must represent a protracted period of geological time. But there is demonstrative evidence that the whole of them had been completed, and that the rocks in which they took place at a great depth had been exposed at the surface by vast denudation before the next member of the pre-Cambrian series was formed. The Torridon sandstone lies with the most complete unconformability on the old gneiss, covering alike its dikes, crush-lines and thrust-planes, by not one of which is it in the least degree affected.

It is of course impossible to form any adequate conception of the length of time denoted by this unconformability. But the more the geologist tries to realize what the denudation of the old gneiss involves, the more impressed will he be with the vastness of the period which it denotes.

Over nearly the whole of the Lewisian gneiss, so far as it has been studied on the mainland, no trace has been found of any rocks save what probably had an eruptive origin. In one district, however, which includes the picturesque valley of Loch Maree, a remarkable group of rocks occurs which, though their exact relations are not without some doubt, appear to indicate a sedimentary series through which the Lewisian gneiss has been erupted. These rocks consist chiefly of fine mica-schist, quartz-schist, graphite-schist and limestone. The graphitic material occurs in bands an inch or more thick in the mica-schist. The limestones are persistent beds, having generally a saccharoid texture, and sometimes full of the usual minerals

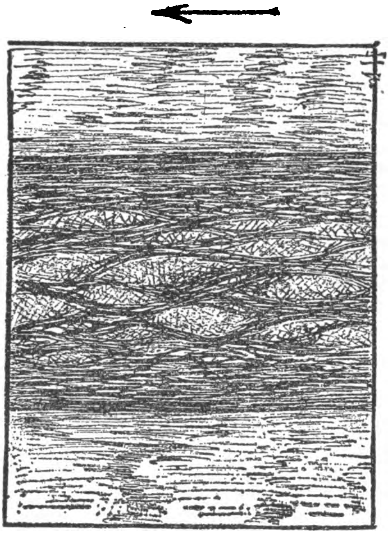

Fig. 382.—Diagram of dolerite dike cutting Lewisian gneiss, representing an area of about 600 square yards.

The dark portion represents the dike with its "eyes" or lenticles surrounded by and passing marginally into hornblende-schist. The gray band on either side of the dike is the surrounding gneiss which has been affected by a secondary foliation parallel to that of the dike. The arrow shows the direction of movement.

found in a marble in a zone of contact-metamorphism. The line of junction of this group of rocks with the gneiss is well defined, but does not distinctly show any intrusion of the latter, appearing rather to have resulted from movement with concomitant crushing. If these strata, so similar in many respects to the undoubted altered sedimentary masses of the central Highlands, are eventually proved to be truly of sedimentary origin they will possess a high interest as the oldest geological formation yet known in Britain or in Europe.[30]

In some portions of the northwest of Scotland, especially in the north of Sutherland, the surface of the gneiss has been reduced, after prolonged denudation, to a kind of

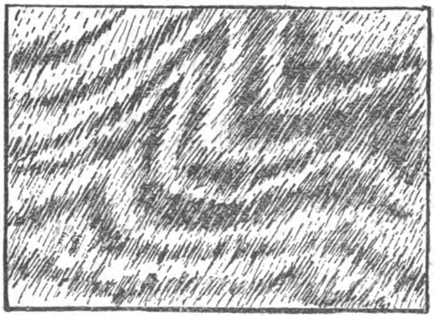

Fig. 383.—Diagram showing later oblique foliation crossing the original banding of the Lewisian gneiss (about nat. size).

level platform on which the Torridon Sandstone has been deposited. But further south that surface presents a singularly uneven character rising into heights 3000 feet above the sea and sinking into hollows that descend below sea-level. In the rugged mountainous ground between Lochs Maree and Broom this primeval land-surface is impressively displayed, for the thick mantle of red sandstone under which it was buried and preserved has been irregularly stripped off, and the details of the pre-Torridonian topography can easily be traced.

TORRIDONIAN.—From Cape Wrath, at the extreme north-west end of Scotland, southward for more than 100 miles, there stretches a broken belt of singular conical or pyra-

[30] See Brit. Assoc. 1891, Sect. p. 634.

midal hills, rising sometimes to more than 3000 feet above the sea, and presenting alike in their form and coloring a striking contrast to the rest of the scenery of that region. They are built up of nearly horizontal or gently inclined strata of reddish-brown or chocolate-colored sandstones and conglomerates, which lie with a violent unconformability on the gneisses above described, and are in turn covered unconformably by the quartzites which form the base of the Cambrian system. Where most fully developed, in the southwest of Ross-shire, these strata are between 8000 and 10,000 feet thick. They have doubtless been derived from the waste of the Lewisian rocks, though pebbles occur in them which have not been identified with any material in the older formation. Some of the conglomerates are so coarse as to deserve the name of bowlder-beds. Sometimes, indeed, where the component blocks are large and angular, as at Gairloch, they remind the observer of the stones in a moraine or in bowlder-clay.[81] Some of the sandstones are in large measure composed of pink felspar derived from such rocks as the pegmatites of the surrounding gneiss. An occasional thin band may be found among them consisting largely of grains of magnetite and zircon, whence we learn at what an ancient epoch in geological history heavy and durable grains were separated out from the more ordinary sediment (see p. 227). In the highest visible portion of these sandstones a group of shales occurs, and another more important group with thin bands of impure limestone forms a prominent feature near the base of the series in the west of Ross-shire. These strata may yet yield recognizable fossils, but hitherto except some tracks and other obscure markings no trace of organic forms has been met with in them.

Messrs. Peach and Horne have detected near Loch Inver a band of fine volcanic tuff among the red sandstones, showing the contemporaneous activity of some volcanic vent in that district. Small vesicular pebbles of porphyrite found among the contents of the conglomerates may perhaps indicate the outflow of lavas.

The strata now under consideration are abundantly displayed among the mountains that surround Loch Torridon, one of the most picturesque inlets in the northwest of Scotland. Hence they were called by Nicol the Torridon Sand-

[81] Nature xxii. 1880, p. 402.

stone. They were originally supposed to be Old Red Sandstone, and to represent the lower sandstones and conglomerates of that system in the east of Sutherland and Ross. After the discovery of what were believed to be Lower Silurian fossils in the Durness limestones, Murchison assigned these sandstones to the Cambrian system. But the recent detection of the Olenellus-zone among the strata which unconformably overlie them proves that they must be of still older date. They are now classed as Torridonian in the pre-Cambrian formations or systems of Britain.

The interval between the deposition of the highest visible portion of the Torridonian series and the base of the Cambrian formations must have been of prolonged duration. For not only had the red sandstones been upraised, but they had been profoundly trenched by denudation. So vast and unequal was the erosion that while at one place the lower quartzites are seen reposing on 3000 or 4000 feet of Torridon sandstone, at another only a few miles distant they rest directly on the Lewisian gneiss, the intervening massive group of strata having been entirely bared away.[32]

But besides the solid areas of pre-Cambrian rocks in the northwest of Scotland there are extensive tracts where these rocks do not remain in their original positions, but have been pushed into their present places by great subterranean disturbances, and have actually been shoved over strata of recognizably Cambrian age. In the account already given (pp. 1036–1041) of the structure of that region it was shown that by these earth-movements slice after slice of the Lewisian gneiss and of the Torridon sandstone has been shorn from the mass of these formations below ground, has been piled one on the other, and has been driven westward over the Cambrian strata which originally lay above them; that the rocks, subjected to such enormous pressure, dislocation and deformation, have undergone serious metamorphism; and that finally by a gigantic rupture and thrust a thick series of gneissose flagstones ("Moine schists") have been brought forward. By way of further explanation of this extraordinary structure the annexed sections are given (Figs. 334, 335). It will be seen what an enormous body of gneiss has here been displaced and pushed over the Cambrian strata, which in turn have been cut into slices and piled up above and against each other. Among the alterations of the

[32] This structure is shown both in Figs. 311 and 334.

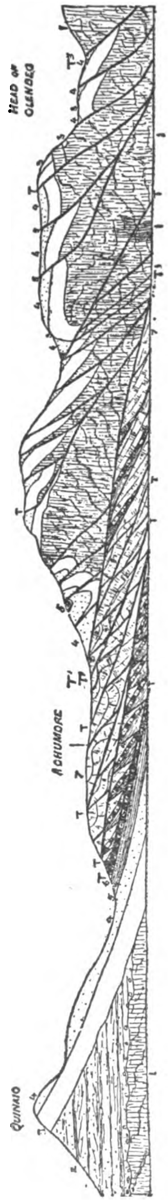

Fig. 334.—Section from Quinaig (2653 feet) eastward through Glasven (2541 feet), Sutherland (Quart. Journ. Geol. Soc. 1888, p. 418). Cambrian.—7. Limestone; 6. Serpulite grit; 5. Fucoid beds; 4, 3. Upper and lower Quartzite. Pre-Cambrian.—2. Torridon Sandstones; 1. Lewisian gneiss. T. Thrust-planes; T'. Maximum Do.

Torridon sandstones one of the most interesting is the production of pegmatitic veins in them, like those which traverse eruptive rocks. These strata have been crushed and stretched in such a manner that ruptures, often lenticular in form, have been produced in them. In the cavities thus caused there has been a deposition of quartz and of quartz and pink felspar (Fig. 335).

With regard to the rocks which have been thus displaced and meta-

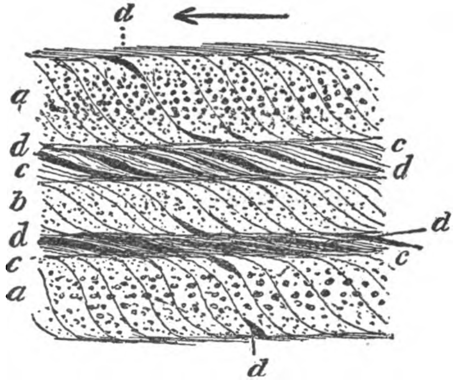

Fig. 335.—Diagram of altered Torridon sandstone, Coinne-mheall, Assynt.

a, Coarse grit or arkose; *b*, finer do.; *c*, shale; *d*, pegmatitic material developed as a consequence of the crushing of the rocks by movement in the direction of the arrow.

morphosed, it is extremely difficult to form a satisfactory opinion as to the probable source and original condition of many of them. Portions of the Lewisian gneiss can be recognized, and in the west of Inverness-shire this rock probably constitutes a large proportion of the reconstructed schistose series which has been thrust westward over the Cambrian limestones and quartzites. The Torridon sandstones also can occasionally be identified, and they may constitute a

not inconsiderable proportion of the "upper gneiss" of western Ross-shire. Possibly other sedimentary material, such, for instance, as any which succeeded the Durness limestones, may have been involved in the gigantic crushing movements that produced the younger or eastern schists. As the detailed work of the Geological Survey advances the sources from which these schists have been derived may be more fully known. But the great fact has been abundantly established that the movements which pushed the rocks into their present positions and imparted to them their existing foliation took place after Cambrian time, and before the period of the Old Red Sandstone. We have thus a notable example of extensive regional metamorphism during the Palæozoic ages.

In the central, southern, and eastern Highlands of Scotland, that is, throughout the hilly ground east and south of the line of the Great Glen, an important series of metamorphic rocks is largely developed, the true stratigraphical position of which is not yet certainly known. They consist in large proportion of altered sedimentary strata, now found in the form of mica-schist, graphite-schist, andalusite-schist, phyllite, schistose-grit, graywacke and conglomerate, quartzite, limestone, and other rocks, together with epidiorites, chloritic schists, hornblende-schists, and other allied varieties which probably mark sills, lava-sheets or beds of tuff, intercalated among the sediments. The total thickness of this assemblage of rocks must amount to many thousand feet. Some of its members are so persistent as to form recognizable horizons, and to afford a basis for some approximation to a stratigraphical arrangement of the whole. In Perthshire, for example, the following groups in descending order have been mapped by the Geological Survey:

Dark schist and limestone (Blair Athol).

Quartzite (Ben-y-Gloe).

Graphite-schist.

Calcareous sericite-schist, and sericite-schist with bands of quartzite. On this horizon occurs a great mass of epidiorite and hornblende-schist.

Garnetiferous mica-schist and schistose pebbly grits.

Limestones (Loch Tay). Hornblende-schists occur above and below this horizon.

Garnetiferous mica-schists, schistose grits, with pebbly bands and thick bands of "green schists." Hornblendic sills begin to appear in this group.

Massive grits with schists and conglomerate containing pebbles sometimes as large as a pigeon's egg. (Ben Ledi, Loch Achray, etc.).

Zone of slates (Aberfoyle).

Pebbly graywacke and grit with black shales and limestone below (Pass of Leny).

The Loch Tay Limestone has now been traced completely across the country from the Moray Firth through the Grampian Mountains to the west of Argyllshire, and some of the other zones have been followed for many miles. The metamorphosed condition of the rocks varies considerably, not only according to their composition, but even along the line of strike of the same group. On the whole the alteration appears to be most intense in the Central Highlands, and to become less as the rocks recede from that area toward the northeast and southwest. One of the most singular and instructive instances of this variation is that which has recently been mapped by J. B. Hill of the Geological Survey in the district of Loch Awe. A series of grits, phyllites, and limestones, resembling ordinary Palæozoic sediments, has there been followed by him northeastward, and has been found to pass along the strike into the thoroughly crystalline schists of the Central Highlands. Mr. Barrow of the Geological Survey has found the metamorphism in Forfarshire to be probably connected with the protrusion of large bodies of granite which often passes into a variety of gneiss. After the great terrestrial movements by which the rocks were folded and metamorphosed, large bodies of eruptive material, notably granite, invaded the schists and produced extensive metamorphism, as already stated (p. 1040). The change is most intense near the granite, where sillimanite imbedded in quartz is a conspicuous mineral in the schists. A little further away comes a band in which kyanite is often abundant, while at a still greater distance the predominant mineral is staurolite. These three successive zones of contact-metamorphism can be found passing through the same band of aluminous schistose material as it recedes from the eruptive rock.

At present no definite opinion can be expressed as to the stratigraphical position of this important group of metamorphic rocks, which forms the greater part of the Highlands of Scotland. On the one hand, it is conceivable that they may all be pre-Torridonian. They may be of the age of the Loch Maree limestones and mica-schists above referred to (p. 1176); or they may represent some part of the vast inter-

val denoted by the unconformability between the Lewisian gneiss and the Torridon sandstone; or again they may possibly include that sandstone and the sedimentary deposits which conformably succeeded it, and which are absent in the Northwest Highlands. On the other hand, they may include, as Murchison believed, representatives of the quartzites and limestones of Durness, and even of later sedimentary formations which may have succeeded these strata, but of which, as we now know, no trace remains in the Northwest Highlands.[33] It is thus still an open question whether the metamorphic rocks which constitute the main part of the Scottish Highlands are of pre-Cambrian or of Cambrian, or even possibly in part of Silurian age. They are not confined to Scotland, but spread over many hundreds of square miles in the north and west of Ireland. As it is convenient to avoid periphrasis by having a short name to designate so important a series of rocks, I have proposed to call them provisionally *Dalradian*, after the old Celtic kingdom of Dalriada, which, originally fixed in the north of Ireland, subsequently extended into the southwest of Scotland, and finally gave the name of Scotland to the kingdom which bears that appellation.[34] I have little doubt, however, that before long it will be possible to make out satisfactorily the structure of the central and southern Highlands, and to show the presence and areas of Lewisian, Torridonian, Cambrian, and even Lower Silurian rocks in that region.

In the north and west of Ireland crystalline schists and eruptive rocks cover a large area; but as the rocks which unconformably overlie them are not of higher antiquity than the Carboniferous and Old Red Sandstone there is no absolute proof in that country of their pre-Cambrian age. There cannot, however, be any doubt that it is the Dalradian series of limestones, quartzites, phyllites, mica-schists, epidiorites, granites, and other crystalline rocks, which crosses from Scotland and spreads across the northern and western counties of Ireland. The Irish development of these rocks is similar to their grouping in Scotland, some of the bands of quartzite, conglomerate, limestone, phyllite, and mica-schist being probably continuations of similar

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[33] Along the Highland border the remarkable band of cherts and igneous rocks referred to on p. 1040 may not improbably show the presence there of the radiolarian cherts and volcanic zone at the base of the Lower Silurian series of the Southern Uplands.

[34] Presidential Address, Quart. Journ. Geol. Soc. xlvii. 1891, p. 75.

bands on the Scottish mainland and in the islands of Argyllshire.[35] But there are also scattered areas of coarsely-banded gneisses which present the closest resemblance to parts of the Lewisian gneiss of Scotland. The best areas for the study of these rocks lie near Pettigoe and Ballyshannon (Donegal), from Erris Head to Blacksod Point (Mayo), in the Slieve Gamph or Ox Mountains stretching from Castlebar beyond Sligo to Manor Hamilton, and in the western part of the County of Galway. The relations of the Dalradian series to the gneisses and granitoid rocks have not yet been accurately determined. But there is reason to believe that the former rests with a violent unconformability upon the latter. Near Castlebar, Mr. A. M'Henry, of the Geological Survey, has recently found at the base of the Dalradian schists a coarse conglomerate made up largely of fragments of the gneisses and granites on which it rests.

In England and Wales many isolated areas have been described as pre-Cambrian on evidence which, as already stated, cannot be considered satisfactory.[36] The areas where in my opinion the most satisfactory evidence of pre-Cambrian rocks can be produced are Anglesey, the Caer Caradoc and Longmynd area and the Malvern Hills. Of these areas by much the most important is the first named. In Anglesey the *Olenellus*-zone has not been discovered, but the fossils found indicate Tremadoc and possibly even Menevian horizons in the Lower Cambrian series.[37] The basement strata are conglomerates, and they evidently lie with a marked unconformability on certain crystalline schistose rocks. It was the belief of Sir A. C. Ramsay that the latter were metamorphosed portions of the Cambrian system, and they were so represented on the Geological Survey maps. But a re-examination of the ground leads to the conclusion that they had acquired their present crystalline characters before the Cambrian strata were laid down upon them; and as these strata belong to a low part, if not the

[35] The fullest account of these Irish metamorphic rocks will be found in the Memoirs of the Geological Survey of Ireland; see especially those on Sheets 1, 2, 5, 6 and 11 (Inishowen, Co. Donegal); 3, 4, 5, 9, 10, 11, 15 and 16 (N.W. and Central Donegal); 22, 23, 30 and 31 (S.W. Donegal); 31 and 32 (S.E. Donegal). See also Harkness, Quart. Journ. Geol. Soc. xvii. 1861, p. 256; Callaway, op. cit. xli. 1885, p. 221.

[36] There is now a voluminous literature on this subject; only some of the more important papers will be here cited.

[37] Prof. Hughes, Quart. Journ. Geol. Soc. xxxvi. 1880, p. 237; xxxviii. 1882, p. 16.

base, of the Cambrian system, it becomes manifest that the schists must be of pre-Cambrian age.[38]

Two groups of schistose rocks, which differ considerably in petrographical characters, have been detected in Anglesey. One of these, consisting mainly of coarse gneisses, abounding in hornblende, garnets, and brown mica, and with coarse pegmatite veins, presents a close resemblance to portions of the Lewisian series of N.W. Scotland. The other group occupies a much larger area, and is composed of flaggy chloritic schists, green and purple phyllites or slates, quartzite, grit, and other more or less recognizably clastic rocks. The resemblance of these masses to the Dalradian series of Scotland and Ireland is striking. The quartzites of Holyhead contain annelid burrows. The exact stratigraphical relations of the two crystalline groups to each other have not yet been satisfactorily determined. There was probably an original unconformability between them, like that referred to as occurring in the west of Mayo.[39] It may be regarded as a well-established fact in British Geology that early in the Cambrian period there existed at least one tract of old crystalline rocks above water in the north-west of Wales.

On the borders of Shropshire and Wales a ridge of ancient rocks rises up from under Silurian strata which lie upon it unconformably. Part of this ridge consists of eruptive material which was formerly believed to be of later date than the sedimentary rocks immediately around. But the main portion of the high ground is formed of a thick series of evidently very old grits, slates, and other clastic deposits, which, though hardly any trace of organic remains had been found in them, were assigned to the Cambrian system. More recent researches, however, have shown the presence of the *Olenellus*-zone in this district at the base of a group of strata which are thus definitely proved to be lower Cambrian.[40]

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[38] Prof. Hughes, op. cit. xxxiv. 1878, p. 137, xxxv. 1879, p. 682; Brit. Assoc. 1881, Sects. p. 643; Proc. Camb. Phil. Soc. iii. pp. 67, 69, 341. Prof. Bonney, Quart. Journ. Geol. Soc. xxxv. 1879, pp. 300, 321; Geol. Mag. 1880, p. 125. Dr. Hicks, Quart. Journ. Geol. Soc. xxxiv. 1878, p. 147; xxxv. 1879, p. 295; Geol. Mag. 1879, pp. 433, 528. Dr. Callaway, Quart. Journ. Geol. Soc. xxxvii. 1881, p. 210, xl. 1884, p. 567. Prof. J. F. Blake, op. cit. xliv. 1888, p. 463; Brit. Assoc. 1888 (Report on Microscopic Structure of Anglesey Rocks).

[39] Quart. Journ. Geol. Soc. xlvii. 1891, Address, p. 82. Mr. Blake has proposed the name of "Monian System" for the pre-Cambrian rocks of Anglesey. In the Address just quoted I have given reasons for my inability to adopt this term.

[40] Lapworth, Geol. Mag. 1888, p. 484.

From this important horizon it is possible to work backward and to show that underlying these basement parts of the Cambrian system a remarkable group of igneous rocks comes to the surface. The investigations of Mr. Allport and Dr. Callaway have shown that these rocks include both lavas and fragmental ejections varying from coarse breccias to fine tuffs. The lavas are generally felsitic in character, showing true rhyolitic structures, but there occur also bands of diabase which may possibly be sills. There is thus clear evidence of a copious ejection of volcanic materials in this part of England before the oldest Cambrian formations were laid down.[41]

Though the evidence is not perhaps conclusive, it seems to point to an unconformability between the base of the Cambrian system and this volcanic group, which would thus probably be of pre-Cambrian date. The relation of the volcanic masses to the great thickness of ancient sedimentary strata constituting the Longmynd ridge has not yet been satisfactorily determined, though there are indications that the volcanic group lies at the bottom. Dr. Callaway has proposed the name *Uriconian* for that group, and *Longmyndian* for the thick series of sedimentary strata lying to the westward. Those names may be provisionally accepted. The Longmyndian rocks have generally been assigned to the Cambrian system, and they may possibly still be shown to belong to that part of the geological record. The Uriconian volcanic group, however, is probably pre-Cambrian.

In other parts of England and Wales isolated areas have been described as containing pre-Cambrian rocks. Of these the district of St. David's in Pembrokeshire has attracted the largest share of attention, chiefly through the labors of Dr. Henry Hicks, who in that small area has endeavored to establish the existence of three distinct pre-Cambrian formations. At the base, under the name of "Dimetian," he places what he considers to be granitoid and gneissic rocks with bands of impure limestone or dolomite, schists and dolerite. Above these he distinguishes as "Arvonian" a group composed essentially of rhyolitic felstones, breccias, and tuffs, marking volcanic eruptions of an acid type, while at the top he describes, by the designation "Pebidian," a

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[41] S. Allport, Quart. Journ. Geol. Soc. xxxiii. 1877, p. 449. C. Callaway, op. cit. xxxiii. p. 652, xxxiv. 1878, p. 754. xxxv. 1879, p. 643, xxxviii. 1882, p. 119, xlii. 1886, p. 481, xlvii. 1891, p. 109; Geol. Mag. 1881, p. 348; 1884, p. 362; 1885, p. 260. J. F. Blake, Quart. Journ. Geol. Soc. xlvi. 1890, p. 386.

series of tuffs and slates.[42] After a careful study of the ground I came to the conclusion that there is no trace of pre-Cambrian rocks at St. David's. I regard the so-called "Dimetian" as a granite which has invaded the Cambrian rocks; the "Arvonian" includes the quartz-porphyries, which appear as apophyses of the granite; while the "Pebidian" is an interesting group of basic lavas and tuffs which form here the lowest visible part of the Cambrian system (referred to at pp. 1212, 1213). A similar group of breccias and tuffs underlies the Cambrian slates of Llanberis, and has likewise been claimed as pre-Cambrian, but it can be shown to pass up continuously into the Cambrian strata. In the Malvern Hills a core of gneissose and schistose rocks is doubtless of pre-Cambrian age, fragments derived from it being found at the base of the overlying unconformable Cambrian strata.[43] From the plains of Leicestershire rises an insular area of rocky hills (Charnwood Forest) composed of slates, tuffs, and various crystalline rocks, which by the Geological Survey have been colored as altered Cambrian. Messrs. Bonney and Hill, who have fully described these rocks, regard them as of pre-Cambrian date, and show to what a large extent they are composed of volcanic agglomerates and tuffs.[44] No conclusive evidence, however, has been adduced that these rocks are pre-Cambrian. The slates resemble some of the Cambrian slates of Wales, and the volcanic rocks may be compared with those which in that principality lie at the base of the Cambrian system. Another protuberance of ancient rocks rises in Central England from beneath the coal-field of eastern Warwickshire. In this instance a definite age can be assigned to one portion of the rocks, for they contain Upper Cambrian fossils.[45] Beneath these strata, and apparently in conformable sequence with them, lies a well-marked volcanic group. The occurrence

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[42] Quart. Journ. Geol. Soc. xxxi. 1875, p. 167, xxxiii. 1877, p. 229, xxxiv. 1878, p. 153, xxxv. 1879, p. 285, xl. 1884, p. 507. My account of the so-called pre-Cambrian rocks of St. David's will be found in Quart. Journ. Geol. Soc. xxxix. 1883, p. 261. Prof. Lloyd Morgan has since confirmed my main conclusions, op. cit. xlvi. 1890, p. 241. Compare also J. F. Blake, op. cit. xl. 1884, p. 294.

[43] J. Phillips, "Geology of the Malvern Hills," Mem. Geol. Surv. ii. part 1; Holl, Quart. Journ. Geol. Soc. xxi. p. 72; Rutley, op. cit. xliii. 1887, p. 481; Callaway, p. 525, op. cit. xlv. 1889, p. 475.

[44] Quart. Journ. Geol. Soc. xxxiii. 1877, p. 754, xxxiv. 1878, p. 199, xxxvi. 1880, p. 337, xlvii. 1891, p. 78.

[45] Lapworth, Geol. Mag. 1886, p. 321; T. H. Waller, op. cit. p. 323; Rutley, p. 557.

of this group in the position which it occupies affords support to the belief that the volcanic rocks elsewhere conjectured to be pre-Cambrian really belong to the Cambrian system. At the Lizard Point in Cornwall a series of eruptive and schistose rocks occurs, the true relations of which have not yet been fixed. They may be pre-Cambrian. They include coarse gneisses which rise as islets near the coast.

On the continent of Europe numerous isolated areas of schists and other ancient rocks have been assigned to a pre-Cambrian or Archæan series. In the older descriptions of these tracts an order of succession was often given, the foliation being assumed to represent consecutive layers of deposition. But we now know that, in the great majority of cases, the foliation is entirely independent of original structure, so that the former attempts to establish a stratigraphical order among the gneisses and schists, and to compare that order in different countries, cannot be accepted. All that can be attempted here is to give a summary of the general characters of the most ancient rocks of each region referred to.

Scandinavia exhibits the largest continuous tract of pre-Cambrian rocks in Europe.[46] Although these rocks have been more or less minutely examined throughout the whole extent of the peninsula, and have been described in many papers and memoirs, the published descriptions of them, though often excellent from the lithological point of view, were almost entirely written before the recent revolution in

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[46] In the older literature consult Keilhau, "Gaea Norvegica," iii. 1850. Kjerulf, "Udsigt over det Sydlige Norges Geologi," Christiania, 1879 (translated into German by Gurlt, and published by Cohen, Bonn, 1880). A. E. Törnebohm, "Die Schwedischen Hochgebirge," Schwed. Akad. Stockholm, 1873. "Das Urterritorium Schwedens," Neues Jahrb. 1874, p. 131. Karl Pettersen, "Geologiske Undersögelser inden Tromsö Amt," etc., Norske Videnskab. Skrift, vi. 44; vii. 261. For more recent work see Reusch's important monograph on the fossiliferous crystalline schists of Bergen, quoted on p. 1031, also his instructive essay "Bömmelöen og Karmöen," 1888; his papers in the "Aarbog for 1891" of the Geological Survey of Norway (Norges Geologiske Undersögelse); his "Geologiske Iagttagelser fra Trondhjems Stift," Christiania vidensk. selsk. forhandl. 1891; and his paper on crystalline schists of Western Norway, Compt. Rend. Congrès Geol. Internat. 1888, 1891, p. 192. T. Dahll, O. A. Corneliussen and H. Reusch, "Det nordlige Norges geologi," Norges Geolog. Undersög. 1892; C. H. Homan, "Selbu," Norges Geolog. Undersög. 1890; and Törnebohm, Nature, 1888, p. 127. It is to be hoped that Prof. Brögger may be able to attack the problem of the schistose rocks of Norway, and that we may have from him such a detailed study of them as he has given us in his memoirs on the Christiania district.

the views of geologists regarding metamorphism, and are therefore without that knowledge of the true meaning of structural characters and that detailed study of the tectonic relations of the rocks which the present condition of the science demands. There can be no doubt that the older crystalline rocks of Scandinavia are a prolongation of those which further to the southwest rise out of the Atlantic in the Highlands of Scotland and the hills of the north and west of Ireland. And there seems every probability that the broad features of geological structure which have been ascertained to prevail in the British area will be found to extend also into Norway and Sweden.[47]

Wide tracts of western Norway consist of coarse banded gneisses (Grundfjeldet, Urberget), which present the closest resemblance to the Lewisian series of Sutherland and Ross, but with a wider range of petrographical diversity. They include red and gray gneisses, banded and streaked granulites, epidote-gneiss, cordierite-gneiss, granites, syenites, gabbros, diorites, labradorite-rocks, garnet-rocks, amphibolites, peridotites, serpentines, etc. The general assemblage of these rocks suggests that they represent a complex series of acid and basic eruptive masses. With them is intimately associated another group of rocks, of which conspicuous members are quartzite, limestone, mica-schist, quartz-schist, and others which point with more or less clearness to a sedimentary origin. This group is usually quite crystalline, and is certainly older than some portions of the gneisses which can be seen to pierce it. It contains, however, bands of amphibolite, which may represent sills intruded between its component layers. Thus at Rukedal (Southern Norway) a mass, 3900 feet thick, of quartzite, quartz-schist, and interbedded seams of hornblende-schist, lies upon a group of hornblende-schists and gray gneiss traversed by abundant granite veins. Thin bands of limestone occasionally occur in the gneiss, as near Christiansand, where they have yielded many minerals, especially vesuvianite, coccolite, scapolite, phlogopite, chondrodite, and black spinel. Apatite with magnetite, titaniferous iron, hæmatite, and other ores forms a marked feature of the Norwegian pre-Cambrian series. The most important mineral masses in an industrial sense

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[47] As the result of two journeys in Norway from Bergen to Hammerfest I was convinced of this general parallelism, but the determination of the detailed stratigraphy of the country will be a task of incredible labor demanding from the Scandinavian geologists many years of patient application.

are thick beds and lenticular masses of iron-ore (Dannemora, Filipstad, etc.).

Of obviously later date than the coarse gneisses with their accompaniments is another series of crystalline schists which spreads over vast tracts of country in Scandinavia. Among these rocks mica-schists, phyllites, quartz-schists, clay-slates, quartzites, and schistose conglomerates are conspicuous, and indicate that a large proportion of the whole mass is probably of clastic origin. But there are also included chloritic and hornblende schists, amphibolites, gneisses, and many other rocks which were probably of eruptive origin, whether injected as sills or thrown out contemporaneously with the sedimentation of the schists as tuffs and lavas. In many respects this important series of schists bears a close resemblance to the "younger gneiss" and Dalradian rocks of Scotland. But its actual stratigraphy has not yet been accurately elucidated. That some portion of it may be pre-Cambrian seems sufficiently probable. But its true relations are complicated by the discovery of Silurian fossils in some portions of the series and by the apparent gradation of comparatively unaltered fossiliferous Silurian strata into the schistose condition. Dr. Hans Reusch of the Geological Survey of Norway has shown that among the crystalline schists to the south of Bergen bands of fine mica-schist or phyllite with layers and nodules of limestone contain fossils probably of Upper Silurian age.[48] I have had an opportunity of visiting the district described by him, have collected fossils from all the localities which he enumerates, and can entirely confirm the account which he gives of the thoroughly metamorphic character of the rocks among which the fossiliferous bands occur. The phyllites are intercalated among white quartzites, quartzite conglomerates, green schists, hornblendic and actinolitic schists and gneisses. But for the occurrence of the fossils, a geologist would naturally class the rocks as probably of pre-Cambrian age. But the corals, graptolites, and other organic remains make it quite certain that the crystalline schists in which they occur underwent their great metamorphism not earlier than some part of the Upper Silurian period. It will be an extremely difficult and laborious task to disentangle the complications of these

[48] "Silurfossiler og pressede Konglomerater i Bergensskifrene," 1882; translated into German by R. Baldauf with the title "Die fossilien-führenden krystallinischen Schiefer von Bergen," Leipzig, 1883.

Norwegian rocks, and to determine which are of pre-Cambrian and which of Palæozoic age. Dr. Reusch, summing up what is known regarding the distribution of fossils among these strata, believes that a more or less continuous belt of Cambrian and Silurian rocks, usually in an extremely metamorphosed condition, can be traced along the axis of the Scandinavian peninsula from near Stavanger to the North Cape.[49] That in this region there were gigantic terrestrial movements with concomitant faults, over-thrusts and metamorphism after Lower Silurian times, is abundantly evident. In southern Norway and in Sweden enormous masses of crystalline schists actually overlie the oldest fossiliferous rocks, as will be described in later pages.

In the east and south of Norway a thick mass of reddish and grayish felspathic sandstone, known there as *Sparagmite*, intervenes between the oldest gneisses (Urberget) and the base of the Cambrian series. It is associated with quartzite and shales, and sometimes becomes strongly conglomeratic. It recalls the Torridon sandstone of Scotland. Probably a large mass of strata, belonging to distinct geographical periods, has been grouped together under the common name of sparagmite. The older sparagmite which underlies the *Olenellus*-zone is probably pre-Cambrian. In western and northern Norway, where the crushing and metamorphism have been so intense, the sparagmite is not recognizable, though it may in an altered condition extend through these regions.

In southern and central Sweden three or four groups of stratified formations, attaining a united thickness of many thousand feet, have been recognized as intermediate between the old gneiss and the lowest portions of the Cambrian system. Their relations to each other have not been very satisfactorily determined, some of them having only a local development. They are distinguished by the following names:

Visingsö group.—Sandstones, red and green shales, limestone and conglomerates. 300 metres. Visingsö on Lake Wettern.

Almesakra group (near Lake Wettern) and Dala Sandstone.—Red and white sandstones and quartzites, sparagmite, red shales and rarely limestone. The Dala Sandstone is believed by Törnebohm to spread over an area of 7150 square kilometres. It attains a thickness of sometimes nearly 900 metres, and contains in the south two well-marked sheets of diabase.

[49] See his sketch-map of Norway and Finland (Geologisk Kart over de Skandinaviske Lande og Finland). Christiania, 1890.

Dalsland group.—Seen in Dalsland only, and composed of an upper group of shales or slates lying on a quartzite series, below which lies a lower shaly series followed by a thick group of sandstones and coarse conglomerates. The total thickness according to Törnebohm is 1900 metres.

Central Europe.—From Scandinavia, a great series of crystalline schists presumed to be pre-Cambrian ranges through Finland[50] into the northwest of Russia, reappearing in the northeast of that vast empire in Petchora Land down to the White Sea, and rising in the nucleus of the chain of the Ural Mountains, and still further south in Podolia. In Central Europe, similar rocks appear as islands in the midst of more recent formations. Among the Carpathian Mountains, they protrude at a number of points. Westward of the central portion of the Alpine chain, they rise in a more continuous belt, and show numerous mineralogical varieties, including gneiss, mica-schist, and many other schists, as well as limestone and serpentine. Some of these rocks are certainly altered sedimentary deposits, others are probably crushed igneous rocks. The protogine of the Alps has been shown by Michel-Lévy to be intrusive. It behaves to the surrounding schists as some parts of the Laurentian gneiss of Canada do to the schists next to that rock.

Pre-Cambrian rocks rise to the surface in a number of detached areas in France, particularly in Brittany, the Cotentin, the central plateau, Morvan, Cevennes, the Pyrenees, the Dauphiny Alps, and the Vosges. In Brittany they have recently been carefully studied by Dr. Barrois, who describes them as largely composed of mica-schists, passing often into gneiss and into quartzite, and including chlorite-schists, amphibolites, talcose and sericitic schists, serpentines, eclogites, and pyroxenites.[51] Extensive masses of granitoid and granulitic gneisses with mica-schists, amphibolites and other crystalline rocks form the foundation of the great central plateau of France. In Brittany, in the central plateau, as well as in other regions of France, thick masses of slates and phyllites occur which by some writers have been placed in the pre-Cambrian series. In the Coten-

[50] The petrographical characters of the vast area of ancient gneiss in Finland are now being carefully mapped and described by the Geological Survey of that country under K. A. Moberg. Each sheet of the map, of which twenty-one have been published up to the present time (July, 1893), is accompanied by an explanatory pamphlet.

[51] Ann. Soc. Geol. Nord, x. xiv. xvi.

tin they are represented by the "Phyllades de St. Lô"—a thick series of hard lustrous slates or phyllites, among which tracks of annelids (?) have been found. By other geologists, however, these rocks are placed in the Cambrian system.

A large area of ancient crystalline schists extends southward from Dresden through Bavaria and Bohemia between the valley of the Danube and the headwaters of the Elbe. Two well-marked groups have been recognized—(*a*) red gneiss, containing pink orthoclase and a little white potash-mica, covered by (*b*) gray gneiss, containing white or gray felspar, and abundant dark magnesia-mica. According to Gumbel the former (called by him the Bojan gneiss) may be traced as a distinct formation associated with granite, but with very few other kinds of crystalline or schistose rocks, while the latter (termed the Hercynian gneiss) consists of gneiss with abundant interstratifications of many other schistose rocks, graphitic limestone, and serpentine. The Hercynian gneiss is overlain by mica-schists, above which comes a vast mass of argillaceous schists and shales. In Bohemia, these overlying crystalline clay-slates and schists ("Etage A" of Barrande) graduate upward into undoubted clastic rocks known as the Pribram Shales, unconformably over which come conglomerates and sandstones lying at the base of the fossiliferous series.[52] The same gradation occurs around the granulite tract of Saxony, where the outer schists may be merely metamorphosed Palæozoic sedimentary rocks.[53]

In the central Pyrenees pre-Cambrian granites, with associated well-stratified masses of gneiss, mica-schist, limestone, etc., are said to occur, but possibly some at least of these rocks are altered Cambrian slates.[54] In Asturias and Gallicia, Barrois has investigated a great series of schists regarded by him as pre-Cambrian, and divisible into two

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[52] For descriptions of the pre-Cambrian rocks of Saxony see Credner, Zeitsch. Deutsch. Geol. Ges. 1877, p. 757; explanations accompanying the sheets of the Geological Survey Map of Saxony, particularly sections Geringswalde, Geyer, Glauchau, Hohenstein, Penig, Rochlitz, Schwarzenberg, Waldheim, Wiesenthal. Bavaria and Bohemia: Gümbel, "Geognostische Beschreibung des Ostbayerischen Grenzebirges," Gotha, 1868; Jokely, Jahr. Geol. Reichsanstalt, vi. p. 355; viii. pp. 1, 516; Kalkowsky, "Die Gneissformation des Eulengebirges" (Habilitationschrift), Leipzig, 1878; Neues. Jahrb. 1880 (i.) p. 29. F. Katzer, "Geologie von Böhmen," 1892.

[53] Lehmann, "Entstehung der altkrystallinischen Schiefergesteine," 1884.

[54] Garrigou, Bull. Soc. Geol. France, i. 1873, p. 418.

important groups—a lower, composed essentially of mica-schists, and an upper, consisting of green chloritous, amphibolitic, talcose or micaceous schists, with subordinate bands of quartzite, serpentine, and cipoline.[55]

America.—In North America the pre-Cambrian rocks, which cover an area estimated at more than 2,000,000 square miles, from the Arctic Ocean southward to the great lakes, have been studied in detail for a longer period than those of any other region, and in many respects they may serve as the type with which those of other parts of the globe may be compared. They were first mapped and described by Logan and Murray in Canada, and were divided by these observers into two distinct divisions. The lower of these, named Laurentian from its extensive development among the Laurentide mountains, was described as consisting chiefly of coarse red, gray, and banded felspathic, hornblendic, micaceous, and pyroxenic gneisses with pegmatites, and included zones of limestone. The upper group, called Huronian from its exposures in the Lake Huron district, was recognized as being composed mainly of quartzites, felsites, diorites, diabases, syenites, various coarse and fine fragmental volcanic rocks (agglomerates and tuffs), clay-slates, and other bedded materials that passed into schists. Though the Huronian series was found along the line of junction to dip below the Laurentian, this position was believed to be due to disturbance, no doubt being entertained that the former series was the younger of the two.

Since the days of these two great pioneers of American pre-Cambrian geology the subject has been attacked by many able observers. The Geological Surveys of Canada and the United States, as well as those of some of the States of the Union, particularly Michigan, Wisconsin, and Minnesota, have examined the rocks over many hundred square miles, and have published voluminous reports concerning them. Unfortunately, as many of the districts were worked out independently, considerable variety of nomenclature and diversity of view have arisen. At present it is hardly possible to reconcile these conflicting opinions, though there can be little doubt that before long a general concurrence will be arrived at regarding the main features of pre-Cambrian geology in this important region. The table on the

[55] Ann. Soc. Geol. Nord, ii. 1882.

next page gives the subdivisions which appear to be best established in the Lake Superior and Lake Huron territory.[56]

According to the general consensus of opinion among the present geologists of the United States and of Canada, the pre-Cambrian rocks of those countries may be divided into two great series. At the base lies a vast mass of gneisses, schists, and eruptive rocks, which, known as the "Fundamental Complex," is regarded as the oldest of the whole. Above this ancient series comes another enormous succession of rocks comprised under the general name of "Algonkian," but consisting of several distinct formations, separated from each other by unconformabilities, as shown here in the table.[57]

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[56] In compiling this table I have been indebted to Mr. C. R. van Hise of the United States Geological Survey for information kindly supplied by him, also to his paper in the Amer. Journ. Sci. and to Mr. Lawson's "Report on the Rainy Lake Region" in the Annual Report of the Canadian Geological Survey for 1887.

[57] Out of the large amount of literature which has grown up concerning the pre-Cambrian rocks of North America the following works may be cited:—W. E. Logan, "Geology of Canada," 1863; Annual Reports of the Geological Survey of Canada, particularly Mr. Lawson's Report on Rainy Lake above cited; Geological and Natural History Survey of Minnesota, vol. ii. Geology, by N. H. Winchell and W. Upham, 1888, and Annual Reports for 1887, 1888, 1891; Geological Survey of Wisconsin, Final Reports, vols. i. ii. iii. iv. by T. C. Chamberlin, R. D. Irving, C. E. Wright, E. T. Sweet, T. B. Brooks, etc.; Geological Survey of Michigan, 1873 (T. B. Brooks), 1881, vol. iv. (C. Rominger), 1891–92, containing a sketch of the geology of the iron, gold and copper districts by M. E. Wadsworth; Second Geological Survey of Pennsylvania, summary volume on Archæan Rocks by J. P. Lesley, 1892; Annual Reports of the United States Geological Survey, especially the 5th and 7th, containing memoirs by R. D. Irving, and the 10th containing a joint memoir by R. D. Irving and C. R. van Hise, and monograph V., on the copper-bearing rocks of Lake Superior by R. D. Irving; Bull. U. S. Geol. Surv. No. 23, T. C. Chamberlin and R. D. Irving; A. C. Lawson, Bull. Geol. Soc. Amer. i. 1890, pp. 163, 175; A. Winchell, op. cit. i. p. 357, ii. p. 85; N. H. Winchell, Proc. Amer. Assoc. xxxiii. 1885; J. D. Whitney and M. E. Wadsworth, "The Azoic System," Bull. Mus. Comp. Zool. Harvard, 1884. C. R. van Hise, Amer. Journ. Sci. xli. 1891, 117; R. Pumpelly and C. R. van Hise, op. cit. xliii. 1892, p. 224. The literature of American pre-Cambrian geology has recently been exhaustively discussed by C. R. van Hise in Bull. U. S. Geol. Surv. No. 86, "Correlation Papers—Archæan and Algonkian," 1892.

TABLE OF THE SEQUENCE OF THE PRE-CAMBRIAN FORMATIONS OF THE UNITED STATES AND CANADA

Algonkian	Keweenawan [Nipigon of W. Ontario].	Detrital rocks derived in large measure from the degradation of the volcanic series below 15,000 feet.
		Sheets of basic and acid lavas, with intercalated masses of sandstone and conglomerate, especially toward the upper part. Said to reach a thickness of 35,000 feet, or more than 6½ miles (?)
		[Unconformability.]
	Upper (original) Huronian [Animikie and Upper Kaministiquia of W. Ontario, Animikie and Upper Vermilion of N. Minnesota, Upper Marquette of Michigan].	Quartzites, carbonaceous and argillaceous shales, slates, conglomerates and ferruginous rocks with intrusive greenstones, at least 12,000 feet. Traces of organisms occur in this series.
		[Unconformability.]
	Lower Huronian [Keewatin, Lower Kaministiquia, Ontario, Lower Vermilion of N. Minnesota, Lower Marquette, Felch Mountain iron-bearing series, Menominee of Michigan].	Limestones, quartzites, phyllites, slates, mica-schists, green chloritic schists, schistose conglomerates, jaspers, iron-ores, diabase and quartz-porphyry lavas, volcanic agglomerates and tuffs with acid and basic intrusions. Probably more than 5000 feet.
		[Unconformability.]
Fundamental Complex.	Coutchiching.	Quartz-biotite mica-schists and fine gray gneisses of remarkably uniform character, estimated by Lawson to be more than 20,000 feet thick in some places, but elsewhere thinner and disappearing.
	Laurentian.	Hornblende-granites and syenites, coarse granitic gneisses and biotite gneisses, some of which have been intruded into the quartz-biotite schists, and even into the base of the group above them.

Mr. Lawson, in his remarkable essay on the Geology of the Rainy Lake region, has brought forward conclusive proof that the Laurentian gneisses invade and alter his Coutchiching schists, and even penetrate in some places into his Keewatin series above. He believes that these gneisses arose from the fusion of the basement or floor on which the overlying formation rested, portions having been absorbed into the magma, and finally appearing with it as gneiss. More recently Messrs. Pumpelly and Van Hise have found on the north shore of Lake Huron clear evidence that the base of the Lower Huronian rocks is marked by a coarse

conglomerate lying with a complete unconformability upon and made up out of the schists, granites, and pegmatites of the fundamental complex.[58]

India.—In India, the oldest known rocks are gneisses which underlie the most ancient Palæozoic formations, and appear to belong to two periods. The older or Bundelkund gneiss is covered unconformably by certain "transition" or "submetamorphic" rocks, which, as they approach the younger gneiss, become altered and intersected by granitic intrusions. The younger or peninsular gneiss is therefore believed to be a metamorphic series unconformable to the older gneiss. In the western Himalayan chain there are likewise two gneisses—a central gneiss, probably Archæan, and an upper gneiss formed by the metamorphism of older Palæozoic rocks into which it passes, and which lie unconformably on the older gneiss and contain abundant fragments derived from it.[59]

China.—Pre-Cambrian rocks are extensively developed in northern China, forming the fundamental masses round and over which the later rocks have been laid down. According to Richthofen, the oldest portions of the series are mica-gneisses and gneiss-granites with hornblende-schists, mica-schists, etc., having an N.N.W. strike and steep inclination. Apparently of later date are some chlorite-gneisses and hornblende-gneisses with intercalations of mica-gneiss and granulite, but without gneiss-granite, seen in north Tshili and north Shansi, and marked by a persistent W.S.W. and E.N.E. strike. These rocks are succeeded unconformably by a great series of groups which may belong to distinct periods. They consist of mica-schists, crystalline limestones, black quartzites, hornblende-schists, coarse conglomerates and green schists. With some of these groups are associated granite, pegmatite, syenite, and diorite. The whole series underwent great plication and denudation before the deposition of the older Palæozoic formations (Sinisian).[60]

Australasia.—In the South Island of New Zealand the most ancient Palæozoic rocks are underlain by vast masses of

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[58] Amer. Journ. Sci. xliii. 1892, p. 224.

[59] Medlicott and Blanford, "Manual of Geology of India," pp. xviii. xxvi. But there are younger Indian schistose rocks, from which these must be distinguished. In the Himalayan region there is a series of gneisses and schists below which lie comparatively unaltered beds of supra-Triassic age.

[60] Richthofen, "China," ii. 1882.

crystalline foliated rocks traceable nearly continuously on the west side of the main watershed. The geological relations of these masses have not yet been satisfactorily defined, and it does not appear to be established whether any portion of them are undoubtedly pre-Cambrian. They are divided by Sir J. Hector into two series, of which the lower consists of gneiss, granite, etc., with an overlying mass of hornblendic, micaceous, and argillaceous schists (probably metamorphosed Devonian); while the upper consists of argillaceous slates and schists, which are regarded as probably altered Silurian or even Carboniferous rocks.[61] In Canterbury there is a central zone of micaceous, talcose, and graphitic schists, overlain by chlorite and hornblende-schists, and lastly by a quartzitic zone interleaved with schists.[62] Crystalline schists and gneisses form the rugged mountainous ground of south-western Otago. The centre of this province is occupied by a broad band of gently inclined mica-schists and slates. These rocks are the main gold-bearing series of Otago.[63]

In Australia, large areas of granite and of crystalline schists occur, but their precise relations have not yet been worked out. Some of these rocks have been described by Selwyn, Ulrich, R. L. Jack, R. A. F. Murray, and others, as probably including metamorphosed Palæozoic formations. But there are not improbably portions of them referable to a pre-Cambrian series.

PART II. PALÆOZOIC

It has been shown in the foregoing pages that though the stratified pre-Cambrian rocks are generally separated by an unconformability from formations of later age, such a break does not always occur, and that in its absence no sharp line of division can be drawn by way of upward limit to the pre-Cambrian series. It is obvious that the physical conditions of sedimentation underwent no universal interruption at the close of pre-Cambrian time, that these conditions had already been established long before the Cambrian period, and that

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[61] "Handbook of New Zealand," by J. Hector, M.D., Wellington, 1883.
[62] Haast's "Geology of Canterbury," p. 252.
[63] Hutton's "Geology of Otago," p. 31.

they were continued in some regions into that period without a break. Moreover, it has now been ascertained beyond doubt that plant and animal life had already appeared upon the earth during pre-Cambrian time. Hence the term Palæozoic, or Primary, which has hitherto been used to denote the older fossiliferous systems that terminate downward at the base of the Cambrian rocks is no longer strictly accurate, unless it is extended so as to include the very oldest strata in which organic remains have been found. Geologists have agreed to fix the base of the Cambrian system at the *Olenellus*-zone, already referred to. It is quite evident, however, that at any moment a new series of fossils may be discovered below that horizon, and it will then be matter for consideration whether such a series should be included in the Cambrian fauna or be made the palæontological basis for the designation of a still older geological system. In the present meagre state of our knowledge regarding these ancient rocks, it seems the most prudent course to take in the meantime the platform of the *Olenellus*-zone, which has now been recognized in many parts of the globe, as the Cambrian basement, and to fix there provisionally the downward limit of the Palæozoic series of systems. That series will thus include all the older sedimentary formations from the bottom of the Cambrian to the top of the Permian system. The strata embraced under the comprehensive designation of Palæozoic consist mainly of sandy and muddy sediments with occasional intercalated zones or thick masses of limestone. They seem everywhere to bear witness to comparatively shallow water and the proximity of land. Their frequent alternations of sandstone, shale, conglomerate, and other detrital materials, their abundant rippled and suncracked surfaces, marked often with burrows and trails of

worms, as well as the prevalent character of their organic remains, show that they must generally have been deposited in areas of slow subsidence, bordering continental or insular masses of land. From the character of the organisms preserved in them, the Palæozoic rocks, as far as the present evidence goes, may be grouped into two main divisions—an older and a newer:—the former, or Silurian facies (from the base of the Cambrian to the top of the Silurian system), distinguished more especially by the abundance of its graptolitic, trilobitic, and brachiopodous fauna, and by the absence of vertebrate remains; the latter, or Carboniferous facies (from the top of the Silurian to the top of the Permian system), marked by the number and variety of its fishes and amphibians, the disappearance of graptolites and trilobites, and the abundance of its cryptogamic terrestrial flora.

Section i. Cambrian (Primordial Silurian)

§ 1. General Characters

In those regions of the world where the relations of the pre-Cambrian to the oldest unmetamorphosed Palæozoic rocks are most clearly exposed and have been most carefully studied, it is seldom that any conformable passage can be traced between these two great rock-groups, though, as already stated, occasional examples of such a gradation occur. More usually a marked unconformability and strong lithological contrast have been observed between the two series, the younger frequently abounding in pebbles derived from the waste of the older. Such a break points to the lapse of a vast interval of time during which the pre-Cambrian rocks, after suffering much crumpling and metamorphism, were ridged up into land and were then laid open to

prolonged denudation. These changes seem to have been more especially prevalent in the northern part of the northern hemisphere. At all events, there is evidence of extensive upheaval of land in the northwest of Europe and across the northern tracts of North America and Northern China[1] prior to the deposit of the earliest remaining portions of the Palæozoic formations. These strata, indeed, were derived from the degradation of that northern land, the extent and height of which may be in some measure realized from the enormous piles of sedimentary rock which have been formed out of its waste. To this day, much of the land in the boreal tracts of the northern hemisphere still consists of pre-Cambrian gneiss. We cannot affirm that the primeval northern land was lofty; but, if it was not, it must have been subjected to repeated renewals of elevation, to compensate for the loss of height which it suffered in the denudation that provided material for the deep masses of Palæozoic sedimentary rock.

The earliest connected suite of deposits in the Palæozoic series received the name "Cambrian" from Sedgwick, who with great skill unravelled the stratigraphy of the most ancient sedimentary rocks of North Wales (Cambria). When the peculiar brachiopodous and trilobitic fauna of Murchison's Silurian system was found to descend into these rocks, the term Primordial Zone or Primordial Silurian was applied to them by Barrande in Bohemia. For many years, however, they yielded so few fossils that their place as a distinct section of the geological record was disputed. Eventually

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[1] The vast erosion of the pre-Palæozoic land is nowhere more impressively shown than in Northern China, where, as Richthofen has pointed out, the oldest gneisses are surmounted by thousands of feet of sedimentary material (Sinisian formation), in the uppermost parts of which Primordial fossils are found. "China," vol. ii.

by the labors of Barrande in Bohemia; Hicks in South Wales; Brögger, Linnarsson, and others in Scandinavia; Schmidt in the Baltic provinces of Russia; Billings, Mathew, Walcott, and others in Canada and the United States, as well as various workers in other countries—such a distinctive fauna has been brought to light as serves to characterize a series of deposits at the base of the Palæozoic formations. This assemblage of fossils, Barrande's first or Primordial fauna, is now by common consent more commonly known as Cambrian. The use of the terms Cambrian and Silurian will be more fully referred to in later pages.

Rocks.—The rocks of the Cambrian system present considerable uniformity of lithological character over the globe. They consist of gray and reddish grits or graywackes, quartzites and conglomerates, with shales, slates, phyllites or schists, and sometimes thick masses of limestone. Their false-bedding, ripple-marks, and sun-cracks indicate deposit in shallow water and occasional exposure of littoral surfaces to desiccation. Sir A. C. Ramsay suggested that the non-fossiliferous red strata may have been laid down in inland basins, and he speculated upon the probability even of glacial action in Cambrian time in Britain.[2] As might be expected from their high antiquity, and consequent exposure to the terrestrial changes of a long succession of geological periods, Cambrian rocks are usually much disturbed. They have often been thrown into plications, dislocated, placed on end, cleaved, and metamorphosed. In Wales they include toward their base an interesting volcanic group consisting of felsitic and diabase-tuffs, and olivine-diabase in interbedded

[2] Q. J. Geol. Soc. xxvii. 1871, p. 250; Proc. Roy. Soc. xxiii. 1874, p. 334; Brit. Assoc. 1880, Presidential Address.

sheets, through which eruptive acid rocks (quartz-felsites, etc.) have risen.

LIFE.—Much interest necessarily attaches to Cambrian fossils, for excepting the few and obscure organic remains obtained from pre-Cambrian strata, they are the oldest assemblage of organisms yet known. They form no doubt only a meagre representation of the fauna of which they were once a living part. One of the first reflections which they suggest is that they present far too varied and highly organized a suite of organisms to allow us for a moment to suppose that they indicate the first fauna of our earth's surface. Unquestionably they must have had a long series of ancestors, though of these still earlier forms such slight traces have yet been recovered.[3] Thus, at the very outset of his study of stratigraphical geology, the observer is confronted with a proof of the imperfection of the geological record. When he begins the examination of the Cambrian fauna, so far as it has been preserved, he at once encounters further evidence of imperfection. Whole tribes of animals, which almost certainly were represented in Cambrian seas, have entirely disappeared, while those of which remains have been preserved belong to different and widely separated divisions of invertebrate life.

The prevailing absence of limestones from the Cambrian deposits of western Europe is accompanied by a failure of the foraminifera, corals, and other calcareous organisms which abound in the limestones of the next great geological series.[4] The character of the general sandy and muddy

[3] Richthofen has suggested that in China possibly some of the deep parts of his "Sinisian" formation (which in its higher parts yields Primordial fossils) may yet reveal traces of still older faunas.

[4] In the Baltic basin some bands of limestone occur in the comparatively thin series of Cambrian strata. In Scotland the Cambrian system includes some 1500 feet of limestone.

sediment must have determined the distribution of life on the floor of the Cambrian sea in that region, and doubtless has also affected the extent of the final preservation of organisms actually entombed. In North America, on the other hand, where thick sheets of Cambrian limestone occur, the conditions of sedimentation have been far more favorable for the preservation of organic forms; hence the known Cambrian fauna of this region exceeds in numerical value that of Europe.

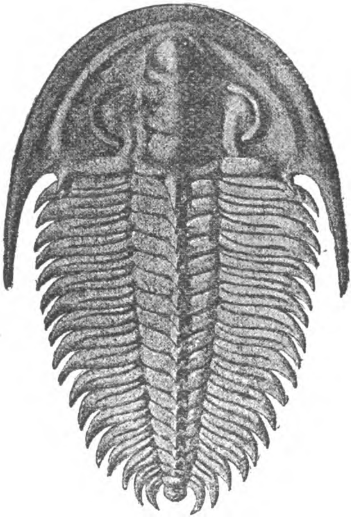

Fig. 336.—Olenellus (O. Callavei, restored by Lapworth), the characteristic genus of the lowest Cambrian strata (ab. ⅛).

The plants of the Cambrian period have been scarcely at all preserved. No vestige of any land plant of this age has yet been detected. That the sea then possessed its seaweeds, can hardly be doubted, and various fucoid-like markings on slates and sandstones (*e.g.* the so-called fucoids of the "fucoid-beds" of N.W. Scotland, and of the "fucoidal sandstone" of Scandinavia) have been referred to the vegetable kingdom. The genus *Eophyton*[5] from Sweden, and others from the Potsdam sandstone of North America, have been described as plants. There seems to be little doubt, however, that of these various markings some are tracks, probably of worms, others are merely imitative

[5] See G. J. Hinde, Geol. Mag. 1886, p. 337; the "fucoids" of the "fucoid-beds" of N.W. Scotland are undoubtedly worm-casts.

wrinkles and markings of inorganic origin.[6] It is not certain that any of them are truly plants. What has been regarded as an undoubted organism occurs in abundance in the Cambrian rocks of the southeast of Ireland, and is named *Oldhamia* (Fig. 338). For many years it was con-

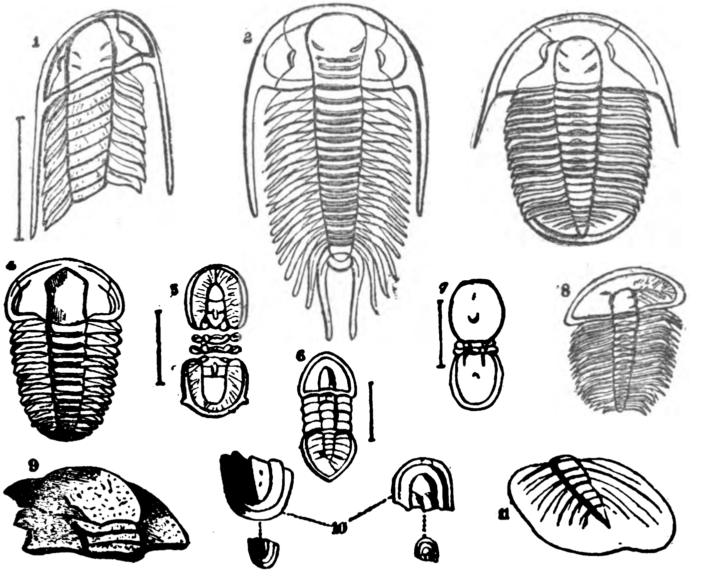

Fig. 337.—Group of Cambrian Trilobites.[9]

1, Olenus impar, Salt. (enlarged); 2, Paradoxides Davidis, Salt. ($\frac{1}{10}$); 3, Conocoryphe (?) Williamsoni, Belt.; 4, Ellipsocephalus Hoffi, Schloth.; 5, Agnostus princeps, Salt. (enlarged); 6, Microdiscus sculptus, Hicks (enlarged); 7, Agnostus Barlowii, Belt. (enlarged); 8, Erinnys venulosa, Salt. 9, Plutonia Sedgwickii, Hicks; 10, Agnostus cambrensis, Hicks (and enlarged); 11, Dikelocephalus celticus, Salt.

sidered to be a sertularian zoophyte, subsequently it was referred to the calcareous algæ; but its true grade seems still uncertain.[7]

Among the a n i m a l organisms of the Cambrian rocks

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[6] See A. G. Nathorst's essay, "Nouvelles observations sur des traces d'Animaux," etc., 4to, Stockholm, 1886.

[9] Where not otherwise stated the figures are of the natural size.

[7] Its claim to be considered organic has even been disputed, but from the manner in which it occurs on successive thin laminæ of deposit I cannot doubt that it is really of organic origin.

the most lowly forms yet detected are hexactinellid sponges, *Protospongia*[8] (Fig. 338), *Leptomytus*, *Trachyum*. The hydrozoa appear in the earliest forms of the tribe of graptolites which played such an important part in Silurian time. Of the Cambrian types, *Dictyograptus* (*Dictyonema*) is one of the most characteristic fossils of the primordial zone of Scandinavia, and other forms are doubtfully referred to *Phyllograptus*, *Climacograptus* and *Dactyloidites*. Casts which are regarded as those left by medusæ on the soft mud of the sea-shore have been noticed in Scandinavia. The Actinozoa of the Cambrian period occur in a number of early types of corals referred to *Archæocyathus*,[10] *Ethmophyllum* and *Spirocyathus*. The Echinodermata are represented by crinoids (*Dendrocrinus*), cystideans (*Protocystites*, Fig. 338, *Eocystites*), and star-fishes (*Palæasterina*, Fig. 339). The crinoids reached their culmination in a variety of forms during Palæozoic time. Though still enormously abundant in individuals on some parts of the present sea-floor, they are but poorly represented there compared with the profusion of their genera and species in the earlier periods of the earth's history. Palæozoic crinoids were distinguished by the vaulted arrangement of accurately fitting plates, by which their viscera were completely inclosed, after the manner of the sea-urchins. The cystideans were so named from the bag-like form in which the polygonal plates inclosing them are arranged.

That annelids existed during the Cambrian period is shown by their frequent trails and burrows (*Arenicolites*, Fig. 338, *Cruziana*, *Scolithus*, *Planolites*, etc.). But the most

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[8] For a description of the character of this earliest sponge, see Sollas, Q. J. Geol. Soc. xxxvi. 1880, p. 362.

[10] Hinde, Quart. Journ. Geol. Soc. xl. 1889, p. 125.

abundantly preserved forms of life are crustacea, chiefly belonging to the extinct order of trilobites (Figs. 336, 337). It is a suggestive fact that these organisms appear even here, as it were, on the very threshold of authentic biological history, to have reached their full structural development. Some of them, indeed, were of dimensions scarcely ever afterward equalled, and already presented great variety

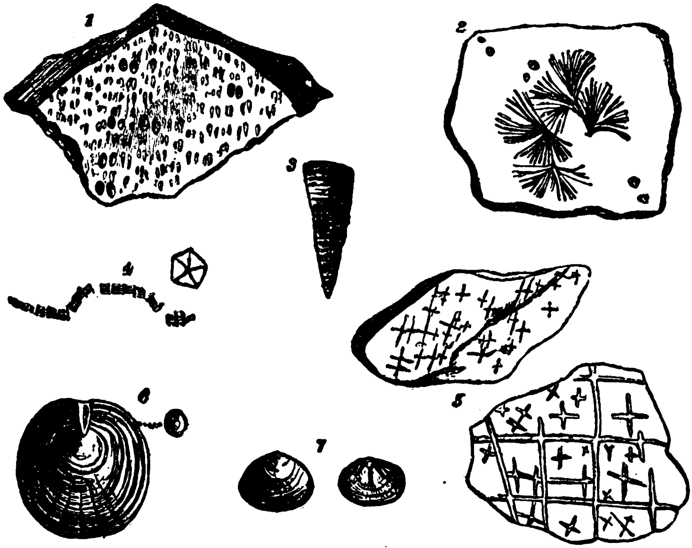

Fig. 338.—Group of Cambrian Fossils.

1, Arenicolites didymus, Salt.; 2, Oldhamia antiqua, Forbes; 3, Theca corrugata, Salt.; 4, Protocystites menevensis, Hicks ($\frac{2}{1}$); 5, Protospongia fenestrata, Salt. (and enlarged $\frac{4}{1}$); 6, Discina pileolus, Hicks (and enlarged); 7, Obolella maculata, Hicks.

of form. Individuals of the species *Paradoxides Davidis* are sometimes nearly two feet long. But with these giants were mingled other types of diminutive size. It is noteworthy also, as Dr. Hicks has pointed out, that while the trilobites had attained their maximum size at this early period, they were represented by genera indicative of almost every stage of development, "from the little *Agnostus*

with two rings in the thorax, and *Microdiscus*, with four, to *Erinnys* with twenty-four," while blind genera occurred, together with those having the largest eyes."[11] In the lower portions of the system the genus *Olenellus* (Fig. 336) is es-

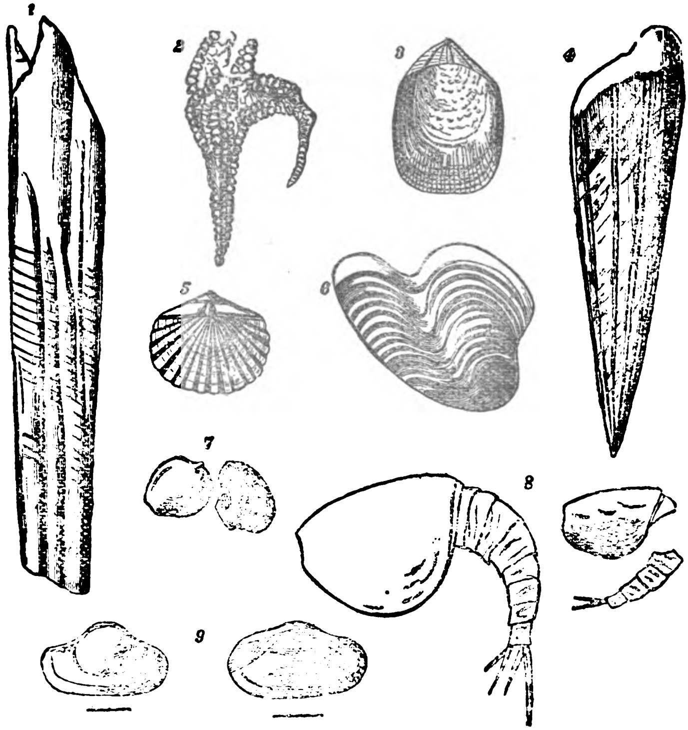

Fig. 339.—Group of Cambrian Fossils.

1, Orthoceras sericeum, Salt.; 2, Palæasterina ramseyensis, Hicks; 3, Lingulella Davisii, McCoy; 4. Conularia Homfrayi, Salt.; 5, Orthis Carausii, Salt.; 6, Bellerophon arfonensis, Salt.; 7, Palæarca Hopkinsoni, Hicks; 8, Hymenocaris vermicauda, Salt. (and enlarged); 9, Ctenodonta cambrensis, Hicks (enlarged).

pecially distinctive. Other characteristic Cambrian genera (Fig. 337) besides those already mentioned are *Plutonia*, *Ellipsocephalus*, *Conocoryphe* (*Conocephalites*), *Anomocare*,

[11] Q. J. Geol. Soc. xxviii. p. 174.

Agraulos, *Ptychoparia*, *Solenopleura*, *Dikelocephalus*, *Olenus*, *Olenoides* and *Anopolenus*. Phyllopod crustaceans likewise occur (*Hymenocaris*, Fig. 339, *Aristozoe*), and there are likewise representatives of the living order of ostracods (*Leperditia*).

In striking contrast to the thoroughly Palæozoic and long extinct order of trilobites, the brachiopods appear in genera of the simple non-articulated group which are still familiar in the living world; but the more highly organized articulate division is also represented. *Lingula* and *Discina* (Fig. 338), which appear among these ancient rocks, have persisted with but little change, at least in external form, through the whole of geological time and are alive still. Other genera are *Lingulella* (Fig. 339), *Acrotreta*, *Obolella* (Fig. 338), *Kutorgina*, *Linnarssonia*, *Orthis* (Fig. 339), and *Orthisina*. Every class of the true mollusca had its representatives in the Cambrian seas. The lamellibranchs occurred in the genera *Ctenodonta* (Fig. 339), *Palæarca* (Fig. 339), *Davidia*, *Modiolopsis*, and *Fordilla*. The gasteropods were present in the heteropod genus *Bellerophon* (Fig. 339), so characteristic of Palæozoic time, also in *Senella*, *Stenotheca*, *Platyceras*, and *Pleurotomaria*. The pteropods were represented by the genera *Hyolithes* or *Theca* (Fig. 338), *Hyolithellus*, *Salterella* and *Conularia* (Fig. 339), the cephalopods by *Orthoceras* (Fig. 339).

Taking palæontological characters as a guide in classification, and especially the distribution of the trilobites, geologists have grouped the Cambrian rocks in three divisions—the lower or Olenellus group, the middle or Paradoxidian, and the upper or Olenidian.

§ 2. Local Development

Britain.[12]—The area in which the fullest development of the oldest known Palæozoic rocks has yet been found is undoubtedly the principality of Wales. The rocks are there of great thickness (12,000 feet or more), they have yielded a fauna which, though somewhat scanty, is sufficient for purposes of stratigraphical correlation, and they possess additional importance from the fact that they were the first strata of such antiquity to be worked out stratigraphically and palæontologically. As already stated, they were called Cambrian by Sedgwick, from their extensive development in North Wales (Cambria), where he originally studied them. Their true base is nowhere seen. Prof. Hughes, Dr. Hicks, Prof. Bonney and others believe that a conglomerate and grit generally mark the base of the Cambrian series.[13] According to Sir A. C. Ramsay, on the other hand, the base of the Cambrian series is either concealed by overlying formations or by the metamorphism which, in his opinion, has converted portions of the Cambrian series into various crystalline rocks. Both in Pembrokeshire and Carnarvonshire the lowest visible slates, shales, and sandstones are intercalated with and pass down into a volcanic series (felsites, diabases, and tuffs) the base of which has not been found. In certain localities, as in Anglesey, Cambrian strata are seen to lie unconformably on pre-Cambrian schists, and there not only the basement volcanic group but some of the lowest members of the fossiliferous series are wanting. There is then not only an unconformable junction, but an overlap.

Starting from the volcanic group at the base the geologist can trace an upward succession through thousands of feet

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[12] See Sedgwick's Memoirs in Quart. Journ. Geol. Soc. vols. i. ii. iv. viii., and his "Synopsis of the Classification of the British Palæozoic Rocks," 4to, 1855; Murchison's "Silurian System" and "Siluria"; Salter's "Cat. of Cambrian and Silurian Fossils," with preface by Sedgwick, 1873; Ramsay's "North Wales," Geological Survey Memoirs, vol. iii.; and papers by Salter, Harkness, Hicks, Hughes and others in the Quart. Journ. Geol. Soc. and Geol. Mag., to some of which reference is made below. J. E. Marr, in his "Classification of the Cambrian and Silurian Rocks," gives a bibliography of the subject up to 1883.

[13] Q. J. Geol. Soc. xxxiv. p. 144; xl. 1884, p. 187. For references to the literature of the subject see the same Journal, xlvii. 1891, Ann. Address, p. 90 *et seq.*

of grits and slates into the Silurian system. Considerable diversity of opinion has existed as to the line where the upper limit of the Cambrian division should be drawn. Murchison contended that this line should be placed below strata where a trilobitic and brachiopodous fauna begins, and that these strata cannot be separated from the overlying Silurian system. He therefore included as Cambrian only the barren grits and slates of Harlech, Llanberis, and the Longmynd. Sedgwick, on the other hand, insisted on carrying the line up to the base of the Upper Silurian rocks. He thus left these rocks as alone constituting the Silurian system, and massed all the Lower Silurian rocks in his Cambrian system. Murchison worked out the stratigraphical order of succession from above, chiefly by help of organic remains. He advanced from where the superposition of the rocks is clear and undoubted, and, for the first time in the history of geology, ascertained that the "Transition-rocks" of the older geologists could be arranged into zones by means of characteristic fossils, as satisfactorily as the Secondary formations had been classified in a similar manner by William Smith. Year by year, as he found his Silurian types of life descend further and further into lower deposits, he pushed backward the limits of his Silurian system. In this he was supported by the general consent of geologists and palæontologists all over the world. Sedgwick, on the other hand, attacked the problem rather from the point of stratigraphy and geological structure. Though he had collected fossils from many of the rocks of which he had made out the true order of succession in North Wales, he allowed them to lie for years unexamined. Meanwhile Murchison had studied the prolongations of some of the same rocks into South Wales, and had obtained from them the copious suite of organic remains which characterized his Lower Silurian formations. Similar fossils were found abundantly on the continent of Europe and in America. Naturally the classification proposed by Murchison was generally adopted. As he included in his Silurian system the oldest rocks then known to contain a distinctive fauna of trilobites and brachiopods, the earliest fossiliferous rocks were everywhere classed as Silurian. The name Cambrian was regarded by geologists of other countries as the designation of a British series of more ancient deposits not characterized by peculiar organic remains, and therefore not capable of being elsewhere satisfactorily recognized. Barrande, investigating the most ancient fossiliferous rocks of Bohemia,

distinguished by the name of the "Primordial Zone" a group of strata forming the lowest member of the Silurian system, and containing a peculiar and characteristic suite of trilobites. Murchison adopted the term, grouping under it the lowest dark slates which in Wales and the border English counties contained some of the same early forms of life.

Subsequent investigations, by the late Mr. Salter and Dr. Hicks, brought to light, from the Primordial rocks of Wales, a much more numerous fauna than they were supposed to possess, and one in some degree distinct from that in the undoubted Lower Silurian rocks. Thus the question of the proper base of the Silurian system was reopened, and much controversy arose as to the respective limits and relative stratigraphical value of the formations to be included under the designations Cambrian and Silurian. No such marked break, either palæontological or stratigraphical, had been found as to afford a clear line of division between two distinct "systems." Those who followed Murchison contended that even if the line of division were drawn at the upper limits reached by the primordial fauna, the Cambrian could not be considered to be a system as well defined and important as the Silurian, but that it ought rather to be regarded as the lower member of one great system comprising the primordial, and the second and third faunas, so admirably worked out by Barrande in Bohemia. To this system they maintained that the name Silurian, in accordance with priority and justice, should be assigned. Unfortunately a disagreement, which was not settled during the lifetime of Sedgwick and Murchison, bequeathed a dispute in which personal feeling played a large part. And though the fires of controversy have died out, it cannot be said that the questions in debate have been left on a wholly satisfactory footing. For myself I repeat what I have said in previous editions of this text-book, that the most natural and logical classification is to group Barrande's three faunas as one system which in accordance with the laws of priority should be called Silurian. But as this arrangement has not been generally adopted in this country I retain the Cambrian in the position which has here been usually assigned to it.[14]

[14] After the first edition of this work was written, in which the future merging of Cambrian and Silurian into one great system was regarded as probable, M. Hébert thus expressed himself: "I adopt the opinion of M. Barrande, based as it was on such thorough and prolonged research, that there is one common character in his three first faunas which unites them into one great whole. To these faunas and the beds containing them I assign the name Silurian, because

The Cambrian rocks of Britain vary widely in mineralogical composition, thickness, and area of exposure in the different districts where they rise to the surface. In North Wales, where they cover the widest extent of ground, they consist of purple, reddish-gray, green, and black slates, grits, sandstones, and conglomerates, with a volcanic group at the bottom, the whole attaining a thickness of probably more than 12,000 feet. In Western England this enormous mass of sedimentary material has dwindled down to a fourth or less, consisting at the base of quartzite and sandstone, and in the upper part of shales. In the east of Ireland, rocks assigned to the Cambrian system resemble on the whole the Welsh type. In the northwest of Scotland, on the other hand, the Cambrian strata, about 2000 feet thick, consist of quartzites below, graduating upward into massive limestones. The following grouping of the British Cambrian rocks has been made:

	WALES (ranging up to 12,000 feet or more)	WESTERN ENGLAND (about 3000 feet)	N.W. SCOTLAND (2000 feet)
Upper or Olenus Zones.	Tremadoc Slates. Lingula Flags (*Linguellea*, *Olenus*, etc.).	Shineton Shales (*Dictyograptus* (*Dictyonema*) *Olenus*, etc.)	A thick mass of limestone divisible into seven groups with *Archæocyathus*, *Maclurea*, *Ophileta*, *Murchisonia*, *Orthoceras*, and vast quantities of annelid castings.
Middle or Paradoxide Zones.	Menevian Group (*Paradoxides*).	Conglomerates and limestones (Comley) with *Paradoxides*, etc.	
Lower or Olenellus Zones.	Harlech and Llanberis group and basement volcanic racks ("Pebidian" of Dr. Hicks, p. 1187), bottom not seen.	Thin quartzite passing up into green flags, grits, shales and sandstone (Comley Sandstone) containing *Olenellus*.	Shales with *Olenellus Salterella*. Quartzites, with annelid burrows (p. 1169).

LOWER.[15]—In South Pembrokeshire the lowest visible Cambrian rocks are of volcanic origin. They consist of fine

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the Silurian fauna was the first to be determined; and, further, I am of opinion that the Cambrian group ought not to appear in our nomenclature as of equal rank with the Silurian group, of which it is merely a subdivision."—Bull. Soc. Geol. France (3) xi. 1882, p. 34. F. Schmidt, also, would prefer to regard the Cambrian as only part of one system extending up to the overlying unconformable Devonian rocks. Q. J. Geol. Soc. xxxviii. 1882, p. 515. My friend Prof. De Lapparent has followed the same principle, making the Silurian system range from the base of the primordial zone to the base of the Devonian rocks. "Traite de Geologie," 3d edit. 1893. See also postea, p. 1229.

[15] The chief authority on the fossils of the Lower Cambrian rocks is the monograph by C. D. Walcott, "The Fauna of the Lower Cambrian or *Olenellus* Zone," published in the 10th Ann. Rep. U. S. Geol. Surv. 1890. This work

tuffs, and silky schists with sheets of olivine-diabase and andesite, and intrusive quartz-porphyries.[16] It is this volcanic group which Dr. Hicks has proposed to class as a pre-Cambrian formation under the name of "Pebidian." In Carnarvonshire the Llanberis Slates, which form the lowest member of the Cambrian sedimentary series, are interleaved at their base with bands of volcanic tuffs and rest upon a mass of quartz-felsite which is the lowest rock visible in the district.[17]

The Olenellus-zone which is the characteristic feature of the lower Cambrian group has not yet been certainly established in Wales.[18] It was first detected in the British Isles by Prof. Lapworth, who in 1885 found fragments of *Olenellus* on the flanks of Caer Caradoc in Shropshire, associated with *Kutorgina cingulata*, *Linnarssonia sagittalis*, *Hyolithellus* and *Ellipsocephalus*.[19] It has been found by the officers of the Geological Survey in the west of Ross-shire, where the following lower Cambrian strata may be traced in a narrow strip of country for a distance of more than 100 miles:[20]

Base of Durness limestones with *Salterella*.

Band of quartzite and grit (Serpulite grit) with abundant *Salterella Maccullochii* and occasionally thin shales with *Olenellus*.

Calcareous and dolomitic shales ("Fucoid beds") with numerous worm-casts usually flattened and resembling fucoidal impressions. *Olenellus* occurs in bands of dark blue shale.

Quartzites, in two divisions, the upper crowded with worm-burrows, the lower becoming pebbly at the base and resting unconformably on pre-Cambrian rocks (Torridonian or Lewisian).

MIDDLE.—This group appears to be most fully developed in South Wales, where it was first studied by Dr. Hicks,

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contains figures and descriptions of this the oldest known distinct assemblage of organisms, and gives a bibliography of the subject up to the year of publication. Some of the other more important memoirs will be cited in subsequent pages.

16 Quart. Journ. Geol. Soc. xxxix. 1883, p. 294, C. Lloyd Morgan, op. cit. xlvi. 1890, p. 241.

17 Op. cit. xlvii. 1891. Presidential Address, p. 90, and authorities there cited.

18 Dr. Hicks believes that it exists there, Geol. Mag. 1892, p. 21.

19 Lapworth, Geol. Mag. 1888, p. 484; 1891, p. 529.

20 Brit. Assoc. Rep. 1891, p. 633. Peach and Horne, Quart. Journ. Geol. Soc. xlviii. 1892, p. 227.

and found to yield a number of characteristic fossils. He has divided it into two groups, the Solva below and Menevian above. From the lower group a number of trilobites, including the typical genus *Paradoxides*, have been obtained, also *Plutonia*, *Microdiscus*, *Agnostus*, *Conocoryphe*. There occur likewise annelids (*Arenicolites*), brachiopods (*Discina*, *Lingulella*), pteropods (*Theca*), and a sponge (*Protospongia*).

The name Menevian was proposed by J. W. Salter and Dr. Hicks for a series of sandstones and shales, with dark-blue slates, flags, and gray grits, which are seen near St. David's (Menevia), where they attain a depth of about 600 feet. They pass conformably into the Lower, and also into the Upper group. They have yielded upward of 50 species of fossils, among which trilobites are specially prominent. *Paradoxides* is the typical genus, while *Agnostus* and *Conocoryphe* are of frequent occurrence. Sponges (*Protospongia*) and annelid-tracks likewise occur. The mollusca are represented by brachiopods of the genera *Discina*, *Lingulella*, *Obolella*, and *Orthis*; and by pteropods (*Cyrtotheca*, *Theca*). An entomostracan (*Entomis*) and cystidean (*Protocystites*) have also been met with.

UPPER.—This highest section of the system has long been divided in Wales into two well-marked groups of strata, the Lingula Flags below and the Tremadoc Slates above. As already stated, its characteristic palæontological feature is the prevalence of trilobites of the genus *Olenus*.

Lingula Flags.—These strata, consisting of bluish and black slates and flags, with bands of gray flags and sandstones, attain in some parts of Wales a thickness of more than 5000 feet. They received their name from the vast numbers of a lingula (*Lingulella Davisii*) in some of their layers. They rest conformably upon, and pass down into, the Menevian group below them, and likewise graduate into the Tremadoc group above. They are distinguished by a characteristic suite of organic remains. The trilobites include the genera *Olenus*, *Agnostus*, *Anopolenus*, *Conocoryphe*, *Dikelocephalus*, *Erinnys*, and *Paradoxides*. Early forms of phyllopods (*Hymenocaris*) and heteropods (*Bellerophon*) occur in these strata. The brachiopods include species of *Lingulella* (*L. Davisii*), *Discina*, *Obolella*, *Kutorgina*, and *Orthis*. The pteropods are represented by species of *Theca*. Several annelids (*Cruziana*) and polyzoa (*Fenestella*) likewise occur.

A subdivision of the Lingula Flags into three sub-groups

has been proposed by Mr. T. Belt, in descending order as follows:[21]

3. Dolgelly slates, about 600 feet, well seen at Dolgelly, consist of soft and hard blue slates and contain *Protospongia*, *Lingulella*, *Orthis lenticularis*, *Olenus scarabœoides*, *O. spinulosus*, *Agnostus trisectus*, *Conocoryphe abdita*.
2. Ffestiniog flags, about 2000 feet, well seen at Ffestiniog, consist of hard sandy micaceous flagstones, and have yielded *Lingulella Davisii*, *Olenus micrurus*, *Hymenocaris vermicauda*, *Bellerophon cambrensis*.
1. Maentwrog flags and slates, about 2500 feet, best seen at Maentwrog in Merionethshire, consist of gray and yellow flagstones, and gray, blue, and black slates, and contain among their somewhat scanty fossils, *Olenus cataractes*, *O. gibbosus*, *Agnostus princeps* (*pisiformis*), *A. nodosus*.

Tremadoc Slates.—This name was given by Sedgwick to a group of dark gray slates, about 1000 feet thick, found near Tremadoc in Carnarvonshire, and traceable thence to Dolgelly in Merionethshire, and reappearing beyond the eastern side of Wales at the Wrekin, in Shropshire.[22] Their importance as a geological formation was not recognized until the discovery in them of a remarkably abundant and varied fauna, which now numbers more than 80 species, including early forms of crinoids, star-fishes, lamellibranchs, and cephalopods. The trilobites embrace some genera (*Olenus*, *Agnostus*, *Conocorphye*, *Dikelocephalus*, etc.) found in the Lingula flags, but include also new forms (*Angelina*, *Asaphus*, *Cheirurus*, *Neseuretus*, *Niobe*, *Ogygia*, *Psilocephalus*). The phyllopods are represented by *Ceratiocaris* and *Lingulocaris*. The same genera, and in some cases species, of brachiopods appear which occur in the Lingula flags, *Orthis lenticularis* and *Lingulella Davisii* being common forms. Dr. Hicks has described 12 species of lamellibranchs from the Tremadoc rocks of Ramsey Island and St. David's, belonging to the genera *Ctenodonta*, *Palœarca*, *Glyptarca*, *Davidia*, *Modiolopsis*. The cephalopods are represented by *Orthoceras sericeum* and *Cyrtoceras prœcox*; the pteropods by *Theca*

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[21] Geol. Mag. 1867, p. 538.
[22] Callaway, Q. J. Geol. Soc. xxxiii. 1877, p. 652. Lapworth, op. cit. 1888, p. 485, 1891, p. 533.

Davidii, *T. operculata*, and *Conularia Homfrayi*; the echinoderms by a beautiful star-fish (*Palæasterina ramseyensis*) and by a crinoid (*Dendrocrinus cambrensis*).[23] Careful analysis of the fossils suggests a separation of the Tremadoc sub-group into two divisions. The most characteristic forms of the lower division are *Niobe Homfrayi*, *N. menapiensis*, *Psilocephalus innotatus*, *Angelina Sedgwickii*, *Asaphus affinis*, and more particularly *Dictyograptus flabelliformis* (*Dictyonema sociale*), which is a characteristic fossil of the uppermost Cambrian rocks in Scandinavia and Russia. The upper division contains *Asaphus Homfrayi*, *Conocoryphe depressa*, and other fossils having a general lower Silurian facies.

It is at the top of the Tremadoc strata that the upper limit of the Cambrian or Primordial formations is now drawn in Britain. The late Sir A. C. Ramsay was of opinion that though no visible unconformability could be seen at this horizon, nevertheless there was evidence on a large scale of the transgressive superposition of the Arenig rocks upon the Tremadoc Slates and Lingula flags below them.[24]

There appears to be more satisfactory proof of a distinct palæontological break at this stage of the geological record in Britain, or at least between the lower and upper part of the Tremadoc sub-group. Up to the present time rather more than seventy species of fossils have been chronicled from the Tremadoc Slates. Of these so far as we know at present only eighteen pass up into the Arenig group above. As these surviving species possess a special interest, in that they connect by a link of continued organic life two great geological periods of such remote antiquity, they are here named—*Arenicolites linearis*, *Asaphus affinis*, *A. Homfrayi*, *Calymene Blumenbachii*, *Cheirurus Frederici*, *Ogygia peltata*, *O. scutatrix*, *O. Selwynii*, *Lingula petalon*, *L. Davisii*, *L. lepis*, *Orthis Carausii*, *O. lenticularis*, *O. Menapiæ*, *Conularia Homfrayi*, *Theca simplex*, *Bellerophon multistriatus*, *Orthoceras sericeum*.[25]

In the northwest of Scotland, the discovery of the *Olenellus*-zone, already referred to, has given a definite geological horizon from which to work out the stratigraphical succession above and below. It has conclusively proved that the thick mass of Torridon sandstone, formerly classed

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[23] Hicks, Quart. Journ. Geol. Soc. xxix. p. 39.
[24] Mem. Geol. Surv. vol. iii. "Geology of North Wales," p. 250.
[25] This list is compiled from Mr. Etheridge's "Fossils of the British Islands," vol. i. 1888.

as Cambrian, must now be relegated to the pre-Cambrian series (ante, p. 1168). Above the quartzite and shales which include the *Olenellus*-zone there lies a series of limestones which attain an aggregate thickness of about 1500 feet. Their original upper limit, however, cannot now be ascertained, for it has been concealed by the great dislocations which have so complicated the structure of that region (see Figs. 311, 334). We cannot tell what additional thickness of limestone may have been accumulated in the northwest at the time when only mud, silt and sand were deposited over the southern parts of the British area, nor by what kind of sediment the limestones were succeeded. The limestones are most fully developed around Durness in the extreme northwest of Sutherland, where they have yielded a large number of fossils. The facies of these fossils, however, is so peculiar that it has not yet been possible by their means to correlate the rocks containing them with the Cambrian formations of Wales. The limestones are so crowded with worm-casts that, as Mr. Peach has pointed out, nearly every particle of their mass must have passed through the intestines of worms. Hence they are obviously of detrital origin, and were probably formed in chief part by small pelagic animals. Only one coral has been found in them. The most abundant fossils are chambered shells (*Orthoceratites*, *Lituites*, *Nautilus*); next in number are gasteropods (chiefly *Maclurea* and *Pleurotomaria*), while the lamellibranchs and brachiopods come last. The bivalves have their valves still united, and the lamellibranchs retain the positions in which they lived. "All the specimens show that every open space into which the calcareous mud could gain access, and the worms could crawl, is traversed by worm-casts. In the case of the *Orthoceratites*, they seem to have lain long enough uncovered by sediment to allow the septa to be dissolved away from the siphuncles which they held in place; many of these siphuncles are now found isolated." Sponges of the genus *Calathium* are scattered through the calcareous sediment, and likewise the doubtful but characteristic Cambrian forms, known as *Archæocyathus*, which, once referred to the sponges, are now thought to be more probably allied to the madrepores. The general assemblage of fossils, as was originally pointed out by Salter, is of a distinctly North American type, and does not resemble that found in the slates, flags, and grits of Wales. The conditions of deposit must have been so entirely different that a great contrast in the organisms of the two areas of sedimentation could not

but occur. Whether or not the contrast further arose from some geographical cause, such as a land-barrier, that completely separated the areas remains uncertain. The Durness limestones, as regards their fossil contents and lithological characters, may be compare with the Potsdam sandstone and Calciferous group of the United States and Canada. They represent the Middle and Upper Cambrian, possibly part of the Lower Silurian formations.[26]

In the southeast of Ireland masses of purplish, red, and green shales, slates, grits, quartzites, and schists occupy a considerable area and attain a depth of apparently several thousand feet without revealing their base, though in Wexford they may possibly rest on pre-Cambrian rocks. Their top is covered by unconformable formations (Lower Silurian and Lower Carboniferous). They have yielded *Oldhamia*, also numerous burrows and trails of annelids (*Histioderma hibernicum*, *Arenicolites didymus*, *A. sparsus*, *Haughtonia pœcila*). In the absence of fossil evidence it is impossible to bring these strata into correlation with those of Wales. Some portions of them have been considerably metamorphosed. On the Howth coast they appear as slates, schists, and quartzites, and include there some remarkable breccias, as well as single blocks of stone scattered through the slates.[27]

Continental Europe.—According to the classification adopted by M. Barrande, the fauna of the older Palæozoic rocks of Europe suggest an early division of the area of this continent into two regions or provinces—a northern province, embracing the British Islands, and extending through North Germany into Scandinavia and Russia, and a central-European province, including Bohemia, France, Spain, Portugal, and Sardinia.

Passing from the British type of the Cambrian deposits, we encounter nowhere in the northern part of the continent so vast a depth of stratified deposits; on the contrary, one of the most singular contrasts in Palæozoic geology is that presented by the development of these formations in Wales, and in the north of Europe. The enormous masses of sediment, thousands of feet thick, and with such uniformity of lithological character, which record the oldest Palæozoic ages in Wales, are represented in the basin of the Baltic by only a few hundred feet of sediments, which show

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[26] B. N. Peach, Quart. Journ. Geol. Soc. xliv. 1888, p. 407.

[27] Quart. Journ. Geol. Soc. xlvii. 1891. Presidential Address, p. 104.

strongly separated lithological subdivisions. Again, while the English and Welsh rocks have been much disturbed and even metamorphosed, those in the eastern part of the Baltic basin remain over wide tracts hardly altered from their original condition of level sheets of sand and clay.

In Scandinavia the Cambrian system lies with a strong unconformability on pre-Cambrian rocks. The so-called "Primordial zone" of this region appears to be everywhere characterized by uniformity of lithological composition as well as of fossil contents, consisting mainly of black shales with concretions or thin seams of fetid limestone. In Scania the following grouping of the Cambrian system has been made, the whole thickness of strata being about 400 Norwegian feet (120 metres).

3. Olenus group. About 200 feet of bituminous fissile alum-shales, with nodules and layers of fetid limestone. The following zones in descending order are noted by S. A. Tullberg—(*k*) zone with *Acerocare ecorne*, (*i*) *Dictyonema flabelliforme*, (*h*) *Cyclognathus mycropygus*, (*g*) *Peltura scarabæoides*, (*f*) *Eurycare camuricorne*, (*e*) *Parabolina spinulosa*, (*d*) *Ceratopyge* sp., (*c*) *Olenus* (the special zone of this genus of which it has many species), (*b*) *Leperditia* sp., (*a*) *Agnostus pisiformis*.

   Professor Brögger has abbreviated this subdivision by making two chief zones, a higher with *Peltura*, *Cyclognathus*, etc., and a lower with *Olenus* (in the strict sense) *Parabolina*, *Eurycare*, etc.

2. Paradoxides group. About 160 feet of sandy shales, alum shales, with three bands of limestone, the lowest ($1\frac{1}{2}$ feet) known as the "Fragmentenkalk," the middle as the "Exsulanskalk," and the highest (2 to 3 feet) the "Andrarumskalk." Mr. Tullberg divides the group into the following zones in descending order, (*m*) *Agnostus lævigatus*, (*l*) *Paradoxides Forchhammeri*. (This is the horizon of the Andrarum limestone, which contains an abundant fauna, including many species of *Agnostus* and other trilobites. (*k*) *Agnostus Lundgreni*, (*i*) *Paradoxides Davidis*, (*h*) *Conocoryphe æqualis*, (*g*) *Agnostus rex*, (*f*) *Agnostus intermedius*, (*e*) *Microdiscus scanicus*, (*d*) *Conocoryphe exsulans*, (*c*) *Agnostus atavus*, (*b*) "Fragmentenkalk" with *Paradoxides ölandicus*, (*a*) Black alum-shale with *Lingulella*, *Acrotreta*, *Obolella*, etc.

Professor Brögger recognizes two chief bands; the higher marked by *Paradoxides Forchhammeri*, the lower by *P. ölandicus*, *P. Tessini*, *P. Davidis*, etc.

1. Olenellus group, consisting of two thin bands of strata, (*b*) Phosphate limestone and sandy shale with *Lingulella*, *Acrothele*, etc., (*a*) Sandy shales passing into sandstone (graywacke-shale) with *Olenellus Kjerulfi*, *Ellipsocephalus Nordenskioldi*, *Arionellus primævus*, *Hyolithes*, etc.[28]

In the Christiania district the lowest stage of the Cambrian series is 90 Norwegian feet thick and is composed of conglomerates, sandstones, and dark shales with limestone. It includes the *Olenellus* zone and that of *Paradoxides*. It is surmounted by an upper stage (150 feet) composed of black slates (alum-shales) and fetid limestone, with *Olenus*, etc. This upper or Olenus stage has been grouped by Brögger into the following five members in ascending order: (*a*) Zone of *Agnostus pisiformis*, *Olenus truncatus;* (*b*) *Parabolina spinulosa* beds; (*c*) *Eurycare latum* beds; (*d*) shales with bands and nodules of limestone, *Peltura scarabæoides;* (*e*) *Dictyograptus* shales with *Dictyograptus* (*Dictyonema*) *flabelliformis*.[29]

Though the Scandinavian Cambrian series is so much thinner than that of Wales, it contains the three distinctive life-platforms recognizable in Britain, and appears thus to be a full palæontological and homotaxial equivalent of the much fuller development of sedimentary material in Britain. The Cambrian type of Southern Sweden undergoes considerable modification as it passes eastward, into the Baltic provinces of Russia. The black shales so characteristic

[28] S. A. Tullberg, Afhand. Sveriges Geol. Undersökn. ser. C. No. 50, 1882. W. C. Brögger, Geol. För. Stockholm Förhandl. No. 101, vol. viii. 1886, p. 196.

[29] For Scandinavian Cambrian rocks see Angelin, "Palæontologica Suecica," 1851–54. Kjerulf, "Geologie des Süd. und Mittl. Norwegen," 1880. Dahll, Vidensk. Selsk. Förhandl. 1867. Nathorst, Kongl. Vet. Akad. Förhandl. 1869, p. 64, and "Sveriges Geologi." Torell, Acta Univers. Lund, 1870, p. 14, Kongl. Vet. Akad. Förhandl. 1871, No. 6. Linnarsson, Svensk. Vet. Akad. Handl. 1876, iii. No. 12: "Om Agnostus-Arterna," etc., Sveriges Geol. Undersökn. ser. C. No. 42, 1880. "De undre Paradoxides lageren vid Andrarum," op. cit. ser. C. No. 54, 1883; Geol. Mag. 1869, p. 393; 1876, p. 145. Tullberg, "Skänes Graptoliter," Sveriges Geol. Undersökn. ser. C. Nos. 50, 55 (1882, 3); Z. Deutsch. Geol. Ges. xxxv, 1883, p. 223. W. C. Brögger, Nyt. Mag. 1876; Geol. Fören. Stockholm Förhandl. 1875–76, 1886, p. 18. "Die Silurischen Etagen 2 und 3 im Kristiania Gebiet, 1882." Lundgren in text to Angelin's Geol. Map of Sweden, N. Jahrb. 1878. Lapworth, Geol. Mag. 1881, p. 260; 1888, p. 484. Marr. Q. J. Geol. Soc. xxxviii. 1882, p. 313. "Classification of the Cambrian and Silurian Rocks," 1883, pp. 72–100.

in Scandinavia thin away, and the distinctive paradoxidian and olenidian divisions disappear. A group of strata, traceable from the S.E. of Lake Ladoga for a distance of about 330 miles to near Baltischport on the Gulf of Finland, with a visible thickness of not more than 100 feet (but pierced to a depth of 600 feet more in artesian wells), consists of three subdivisions; (*a*) Blue clay composed of a lower set of iron-sandstones (300 feet) resting on granite and an upper blue clay (300 feet), formerly noted only for some obscure fossils (*Platysolenites*, Pander, probably fragments of cystideans) but now known to include the *Olenellus*-zone; (*b*) Ungulite grit (50 to 60 feet) containing *Obolus Apollinis* (*Ungula*, Eichw.), *Schmidtia celata*, etc.; (*c*) *Dictyonema*-shales (about 20 feet) with *Dictyograptus* (*Dictyonema*) *flabelliformis*.[30] The recent researches of Schmidt have clearly shown the relations between these soft and seemingly not very old deposits and the Cambrian system of the rest of Europe. The lower sandstone, blue clay and a fucoidal sandstone lying immediately above the latter form an unequivocally Lower Cambrian group, for they have yielded *Olenellus Mickwitzi*, *Scenella discinoides*, *Mickwitzia monilifera*, *Obolella*, *Discina*, *Volborthella* (doubtfully referred to the orthoceratites), *Platysolenites* and *Medusites*. Schmidt points out that a complete break occurs between the top of the fucoid sandstone and the base of the Ungulite sandstone, and that this hiatus represents the Paradoxidian and Olenidian groups, while the Dictyonema-shales form the characteristic uppermost zone of the system.[31]

In Central Europe, Cambrian rocks appear from under later accumulations in Belgium and the North of France, Spain, Bohemia, and the Thuringer Wald.[32] The most important in France and Belgium is that of the Ardennes,[33] where the principal rocks are grit, sandstone, slates, and schistose quartzites or quartz-schists (quartzo-phyllades of Dumont), with bands of whet-slate, quartz-porphyry, dia-

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[30] F. Schmidt, Quart. Journ. Geol. Soc. xxxviii. 1882, p. 516.

[31] Mem. Acad. Imp. Sci. St. Petersbourg, xxxvi. 1889, No. 2.

[32] The student will find a useful compendium on the correlation of the Cambrian and Silurian rocks of western Europe by S. Törnquist in Geolog. Fören. Stockholm Förhandl. xi. 1889, p. 299.

[33] Dumont, "Memoires sur les Terrains Ardennais et Rhénan," 1847-48. Dewalque, "Prodrome d'une Description Geol. de la Belgique," 1868. Mourlon, "Geologie de la Belgique," 1880. Gosselet, "Esquisse Geol. du Nord de la France," etc., 1880, and his great Monograph, "L'Ardenne," Mem. Carte Geol. detaill. 4to, 1888.

base, diorite, and porphyroid. According to Dumont these rocks, comprehended in his "Terrain Ardennais," can be grouped into three great subdivisions—1st and lowest the "Système Devillien," pale and greenish quartzites with shales or phyllades, containing *Oldhamia radiata* and annelid tracks (*Nereites*); 2d, the "Système Revinien," phyllades and black pyritous quartzites from which *Dictyograptus flabelliformis* (*Dictyonema sociale*), and worm-burrows have been obtained; 3d, the "Système Salmien," consisting mainly of quartzose and schistose strata or quartzo-phyllades, and yielding *Dictyograptus flabelliformis*, *Chondrites antiquus* and *Lingula*. The Devillian and Revinian divisions are united by Gosselet into one series composed of (*a*) Violet slates of Fumay; (*b*) Black pyritous shales of Revin; (*c*) magnetite slates of Deville; (*d*) Black pyritous shales of Bogny. These rocks have been greatly disturbed. They are covered unconformably by Devonian and later formations. In the northwest of France extending through the old provinces of Brittany, the west of Normandy and the north of Poitou, a great isolated mass of ancient rocks rises out of the plains of Secondary formations, and the pre-Cambrian rocks already referred to are there succeeded, with a more or less distinct unconformability, by a thick series of sedimentary groups which are now considered to be of Cambrian age. In western Brittany the pre-Cambrian green silky schists known as the "Phyllades de Douarnenez," which are believed to be about 3000 metres thick, are followed, perhaps unconformably, by purple conglomerates, sometimes 530 metres thick, and passing up into red shales which have a vertical depth of 2500 metres, and are surmounted by the Grès Armoricain or bottom of the Silurian system. In these strata *Scolithus* and *Tigillites* occur, but recognizable fossils are extremely rare, and no trace has yet been found here of the more typical Cambrian forms. In the basin of Rennes considerable bands of limestone, sometimes magnesian, together with quartzites, conglomerates, and graywackes occur in the Cambrian series. In the region of the Sarthe basement conglomerates are followed by gray shales with thick bands of siliceous and magnesian limestone, above which lies a series of sandy rocks containing *Lingula crumena* and passing under the Grès Armoricain.[34] In southern France from the Cambrian rocks which

[34] The (pre-Cambrian) phyllades of Brittany and the (Cambrian) purple conglomerates and red shales which succeed them were exhaustively treated by

flank the isolated pre-Cambrian axis of upper Languedoc the most satisfactory fossil evidence has recently been obtained, showing the existence there of both the Paradoxidian (*Paradoxides*, *Conocoryphe*) and Olenidian divisions of the Cambrian system.[35] Among the French Pyrenees, narrow strips and patches of strata have been detected which, lying below fossiliferous Lower Silurian rocks, are believed to be Cambrian.[36]

In various parts of Spain, indications of the presence of Cambrian rocks are furnished by Primordial fossils. In the province of Seville the highest beds have yielded *Archæocyathus*, and in the province of Ciudad-Reale, Primordial trilobites (*Ellipsocephalus*). But it is in the Asturias that the most abundantly fossiliferous rocks of this age occur. They are grouped by Barrois into (*a*) Slates of Rivadeo, blue phyllades and green slates and quartzites, in all about 3000 metres, and (*b*) Paradoxides beds of La Vega (50 to 100 metres) composed of limestones, slates, iron-ores, and thick beds of green quartzite. In the upper part of (*b*) a rich Primordial fauna occurs, comprising a cystidean (*Trochocystites bohemicus*) and trilobites of the genera *Paradoxides*, 2 species, *Conocoryphe* (*Conocephalites*), 3 species, and *Arionellus*, 1 species.[37]

In the Thuringer Wald certain phyllites, clay-slates, quartzites, etc., passing up into strata containing Silurian fossils are referred to the Cambrian system. The quartzites have yielded some indistinct fossils referred to *Davidia* and *Lingula*.[38] But it is in Bohemia that the central European type of the Cambrian system is best developed. The classic researches of Barrande have given to the oldest fossiliferous rocks of that country an extraordinary interest. At the base of the Bohemian geological formations lie the slates which Barrande placed as his Étage A (Przibram

Hébert, Bull. Soc. Geol. France, (3) xiv. 1886, p. 713. See also, Tromelin et Lebesconte, Bull. Soc. Geol. France, iv. 1876, p. 583; Tromelin, Assoc. Française, 1879, p. 493, Lebesconte, Bull. Soc. Geol. France (3) x. p. 55, xix. 1891, p. 15, Guillier, op. cit. (3) ix. p. 374; Barrois, op. cit. v. 1877, p. 266, Carte Geol. France, Redon sheet.

[35] J. Bergeron, Bull. Soc. Geol. France, xvi. 1888, p. 282, "Étude geologique du massif aucien au sud du Plateau central," 1889.

[36] J. Caralp, "Études geol. sur les hauts massifs des Pyrenées centrales," 1888, p. 452. E. Jacquot, Bull. Soc. Geol. France, 1890, p. 640.

[37] Barrande, Bull. Soc. Geol. France (2) xvi. p. 543. Macpherson, Neues Jahrb. 1879, p. 930. Barrois, Mem. Soc. Geol. Nord, ii. 1882, p. 168.

[38] H. Loretz, Jahrb. Preuss. Geol. Landesanst. 1881, p. 175. Marr. Geol. Mag. 1889, p. 411.

schists), and which are no doubt pre-Cambrian. They are overlain by vast masses of conglomerates; quartzites, slates, and igneous rocks (Etage B), which have been more or less metamorphosed, and are singularly barren of organic remains, though some of them have yielded traces of annelids (*Arenicolites*). They pass up into certain gray and green fissile shales, in which the earliest well-marked fossils occur. The organic contents of this Etage C or Primordial zone (300 to 400 metres thick) form what Barrande termed his Primordial fauna, which yielded him 40 or more species, of which 27 were trilobites, belonging to the characteristic Cambrian genera: *Paradoxides* (12), *Agnostus* (5), *Conocoryphe* (4), *Ellipsocephalus* (2), *Hydrocephalus* (2), *Arionellus* (1), *Sao* (1). Not one of these genera, save *Agnostus* (of which four species appear in the second fauna), were found by Barrande higher than his Primordial Zone. Among other organisms in this Primordial fauna, the brachiopods are represented by species of *Orthis* and *Orbicula*, the pteropods by *Theca*, and the echinoderms by cystideans. It is worthy of note that the fossil contents of the zone on the opposite sides of the little Bohemian basin were found by the same great pioneer to be not quite the same, only eight species of trilobites being common to both belts, while no fewer than 27 species were detected by him only on one or other side. The Olenidian trilobites which characterize the upper Cambrian group were not observed by him in Bohemia.[39] More recent researches have modified some of the stratigraphical details of his work, the geological structure of the country having been found to be much less simple than he supposed. But the fundamental grouping which he established remains much as he left it. A portion of his Stage B, the whole of his Primordial zone (Stage C), and a part of the base of his Stage D (Lower Silurian), have been grouped together by Dr. Katzer in four members as the Cambrian development in Central Bohemia thus: (*a*) Basement conglomerates, (*b*) Paradoxides shales, (*c*) Quartz-graywacke group, (*d*) Diabase and red-iron-ore group.[40] The Olenellus-zone has not been noticed.

In Sardinia a characteristic assemblage of Cambrian fos-

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[39] See his colossal work, "Système Silurien de la Bohême," published in successive parts and volumes from 1852 up to his death in 1883; also Marr, Quart. Journ. Geol. Soc. xxxvi. 1880.

[40] F. Katzer, "Das ältere Palæozoicum in Mittelböhmen," Prague, 1888; "Geologie von Böhmen," Prague, 1892, p. 804.

sils has been described by Prof. G. Meneghini, comprising three species of *Paradoxides*, six of *Conocephalites*, five of *Anomocare*, five of *Olenus*, as well as other forms.[41]

North America.—During the last decade a large amount of attention has been paid by the geologists of the United States and of Canada to the study of stratigraphy and fossil contents of the Cambrian rocks of North America, and the result of their labors has been to show that, whether as regards extent and thickness of strata, or variety and abundance of organic remains, these rocks surpass in importance the corresponding European series. The European types of sedimentation are replaced by a varied assemblage of materials, among which limestone plays a large part; and this change, as might be expected, is accompanied by a remarkable contrast in the general facies of the fossils. Nevertheless, the leading type-genera of Europe have been found in their usual sequence, so that it has been possible to subdivide the American Cambrian system into three groups which can be broadly correlated with the threefold arrangement adopted in Europe.

From the straits of Belle Isle the Cambrian formations of North America run through Newfoundland and Nova Scotia into New Brunswick. From the eastern coast of Gaspé they stretch along the right bank of the St. Lawrence to Lake Ontario. In several approximately parallel bands they range through the northeastern states of the Union, spreading out more widely in the north of New York State, and in Vermont and eastern Massachusetts. They rise along the Appalachian ridge, striking through Pennsylvania, Maryland, Virginia, Tennessee, and Georgia, down into Alabama, to a distance in the eastern part of the continent of about 2000 miles. In the heart of the continent, again, they rise to the surface, and, flanking the vast pre-Cambrian region of the north, extend over a wide area between Lake Superior and the valley of the Mississippi in the States of Michigan, Wisconsin, and Minnesota. An isolated tract of them is found in Missouri, and another in Texas. The great terrestrial movements which ridged up the Rocky Mountains and their offshoots have brought the Cambrian rocks once more to the surface from under the vast pile of younger formations beneath which, during a large part of geological time, they lay buried. Hence along the axes of these elevations of the terrestrial crust they can be traced in many lines of outcrop

[41] Memorie per serv. alla descriz. della Cart. Geol. d'Italia, III. part 2, 1888.

from Arizona northward through Utah, Colorado, Nevada, Wyoming, Dakota, and Montana, whence they strike far northward into the Dominion of Canada.

In thickness and lithological character the Cambrian rocks of North America exhibit considerable variation as they are traced across the continent, and these changes afford interesting evidence of the geographical conditions and geological revolutions of the region in the early ages of Palæozoic time.[42] In Newfoundland, where the three groups of the system have been recognized, the total depth of strata measured by A. Murray was about 6000 feet, of which the Lower division forms only about 200 feet. In western Vermont and eastern New York the total depth of the system seems to be about 7000 feet; and of this great mass of sedimentary material the lower division may occupy perhaps as much as 5000 feet.[43] Over the central parts of the continent west of the line of the Mississippi the thickness diminishes to 1000 feet or less; but again to the west of the Rocky Mountains it increases to 7000 feet or more in Nevada, while in British Columbia it rises to 10,000 feet.

In the northeastern regions the sediments were chiefly muddy, and are now represented by thick masses of shale with a little sandstone and limestone. The limestones increase in number and thickness southward in Vermont, where a considerable mass of calcareous material lies in the lower group below several thousand feet of shale. Still further south the lower group consists largely of sandstones, which are followed by sandy, dolomitic, and purely calcareous limestones. In Nevada, where a thickness of 7700 feet has been assigned to the Cambrian system, the limestones are 4250 feet in aggregate thickness.[44]

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[42] Among writers on the Cambrian palæontology of North America a high place must be assigned to James Hall, E. Billings, C. D. Walcott and G. F. Mathew. Mr. Walcott has devoted himself to the subject with untiring enthusiasm and much skill. His most important memoirs will be found in the Bulletins of the U. S. Geological Survey, Nos. 10, 1884, 30, 1886, 81, 1891, and in the 10th and 12th Annual Reports, 1890. He gives a full bibliography. Of great importance also are the memoirs on the Cambrian rocks and fossils of Canada, by Mr. Mathew, published in the Trans. Roy. Soc. Canada, from the first volume 1882 onward.

[43] Walcott has found Olenellus about 2000 feet below the summit of the series, but he hesitates to assume that it can really range through such an enormous thickness of strata, 10th Ann. Rep. U. S. Geol. Surv. p. 583. See his later section in 12th Ann. Rep. 1892, plate xlii.

[44] A. Hague, Ann. Rep. U. S. Geol. Surv. 1881–82. Walcott, Monogr. U. S. Geol. Surv. vol. viii. 1884.

It will be seen, therefore, that the nearest European parallel to the combination of thick arenaceous with thick calcareous accumulations, which distinguishes the Cambrian system of North America, is to be found in the northwest of Scotland. In this connection it is interesting to note that the general facies of the Scottish Cambrian fossils, so distinct from that of the rocks of Wales and the rest of Europe, and so much more akin to that of the United States and Canada, is accompanied by a markedly North American type of sedimentary material.

The following table gives the latest classification of the Cambrian system of North America:[45]

Upper or Potsdam (Olenus and Dikelocephalus fauna).	Sandstones of N. and E. sides of Adirondack Mountains of New York and adjacent parts of Canada. On the same horizon lie the limestones S. of Adirondacks and Dutchess County, New York; and the shales of Tennessee, Georgia and Alabama. In the west come the sandstones of the Upper Mississippi Valley, S. Dakota, Wyoming, Montana and Colorado, the sandstones and calcareous beds of N. Arizona, and the limestones and shales of Nevada. In the far northeast are the black shales at the top of the New Brunswick and Cape Breton Island Sections, and the shales and sandstones of Conception Bay, Newfoundland (Belle Isle).
Middle or Acadian (Paradoxides fauna).	Shales and slates of Eastern Massachusetts (Braintree), New Brunswick (St. John), and Eastern Newfoundland (Avalon). With these typical rocks are correlated part of the limestones of Dutchess County, New York (Stissing) and the central parts of the Tennessee and Alabama sections (Coosa), with limestones in central Nevada and British Columbia (Mount Stephen).
Lower or Georgian (Olenellus fauna).	The typical locality is in western Vermont where shales and limestones are developed. With these are paralleled the quartzite of W. slope of Green Mountains and Appalachian chain in Pennsylvania, Virginia, Tennessee, Georgia, and Alabama; the shales and interbedded limestones and slates of S. Vermont and New York southward to Alabama; the limestone, sandstone and shale of Straits of Belle Isle (Labrador), N.W. Coast of Newfoundland and peninsula of Avalon (Placentia); the basal series of Hanford Brook Section, Caton's Island, etc., New Brunswick; the shales and limestones of E. and S. Massachusetts (Attleborough); the lower portion of the Eureka and Highland ranges, Nevada (Prospect); a portion of the Wahsatch Cambrian Section (Cottonwood) and the base of the Castle Mountain, British Columbia.

A large assemblage of fossils has been obtained from the Cambrian rocks of North America. The fauna of the Olenellus-zone has been fully described in a separate monograph by Mr. Walcott. The middle group in New Brunswick (St. John) has also yielded an abundant fauna which has been described by Mr. Mathew.[46]

[45] C. D. Walcott, Bull. U. S. Geol. Surv. No. 81, 1891, p. 360.

[46] Walcott, 10th Ann. Report U. S. Geol. Surv. 1890, where plates and de-

South America.—In the northern part of the Argentine Republic a representative of the Upper Cambrian or Olenus group has been found by Lorentz and Hyeronimus. It includes species of the genera *Lingula*, *Obolus*, *Orthis*, *Hyolithes*, *Arionellus*, *Agnostus*, and *Olenus*.[47]

China.—Baron von Richthofen has brought to light a succession of undisturbed strata (his "Sinisian formation") which in Leao-tong and Corea attain a thickness of many thousand feet. In the higher parts of this series he found a characteristic assemblage of Primordial trilobites: *Conocoryphe* (*Conocephalites*) (4 sp.), *Anomocare* (6), *Liostracus* (3), *Dorypyge* (*Olenoides?*), *Agnostus* (1), with the brachiopods *Lingulella* (2) and *Orthis* (1).[48]

India.—In the Salt Range, among shales (Neobolus beds) underlying magnesian sandstones and shales with pseudomorphs of salt, and overlying purple sandstones, with a group of beds of rock-salt and gypsum, Cambrian fossils have been detected. They include a number of brachiopods (*Lingula*, *Davidsonella*, *Neobolus*, etc.) and two trilobites, one of which has been determined to be a *Conocephalites*, nearly related to *C. formosus* from the St. John's group (p. 1228), while the other is probably an *Olenus*.[49]

Australia.—In the southeast of this continent and in Tasmania traces of the existence of a Cambrian fauna have recently been detected. Mr. R. Etheridge, Jr., has described from that region forms of *Conocephalites*, *Asaphus*, *Dikelocephalus* and *Ophileta*, and some species belonging to the family of Archæocyathinæ.[50]

Section ii. Silurian

Murchison was the first to discover that the so-called "Transition rocks" or "Grauwacke" of early geological lit-

scriptions of the fossils will be found. See also his papers in Bull. U. S. Geol. Surv. Nos. 10 and 30. For the fossils of the St. John division consult the papers of G. F. Mathew, quoted on p. 1227.

[47] E. Kayser, "Beiträge zur Geol. u. Palaeont. d. Argentinischer Republik. Part II. 1876.

[48] Richthofen, "China," vol. iii. 1882. W. Dames compares this Chinese Cambrian fauna with that of the Andrarumskalk of Scandinavia: op. cit. p. 32 (ante, p. 1219). Mr. Walcott inclines to believe that the fossils rather point to a Middle Cambrian fauna (Bull. U. S. Geol. Surv. No. 81, 1891, p. 379).

[49] Palæontologia Indica, ser. 13, vol. i. 1887, p. 750.

[50] Proc. Roy. Soc. Tasmania, 1882–83, p. 151; Trans. Roy. Soc. South Australia, xiii. 1890, p. 10.

erature were capable of subdivision into distinct formations characterized by a peculiar assemblage of organic remains. As he found them to be well developed in the region once inhabited by the British tribe of Silures, he gave them the name of Silurian.[51] From the base of the Old Red Sandstone, he was able to trace his Silurian types of fossils into successively lower zones of the old "Grauwacke." It was eventually found that similar fossils characterized the older sedimentary rocks all over the world, and that the general order of succession worked out by Murchison could everywhere be recognized. Hence the term Silurian came to be generally employed to designate the rocks containing the first great fauna of the Geological Record.

The controversy regarding the respective limits of the Cambrian and Silurian formations (ante, p. 1211) survived the lifetime of the two great antagonists. Prof. Lapworth in 1879 proposed, as a compromise, that the lower half of Murchison's Silurian system, which Sedgwick had claimed as Cambrian, should be detached from both and erected into a distinct system under the name "Ordovician." [52] I consider that this proposal, which was honestly intended to obviate confusion and to promote the progress of the science, is fair to neither of these fathers of English geology, and is espepecially unjust to Murchison. The division of "Lower Silurian" has the claim not only of priority, but of having been established and of having had its component members defined by the author of the Silurian system in the early years of his investigation. The primordial fauna which Barrande had shown to underlie the Lower Silurian rocks of Bohemia was hardly known to exist in Britain during Murchison's

[51] Phil. Mag. (3), vii. 1835, p. 47. [52] Geol. Mag. 1879, p. 13.

life, and certainly was not then ascertained to have the stratigraphical significance and wide geographical diffusion which have now been proved. It is universally admitted that this fauna marks a distinct section of the geological record to which by common consent the name Cambrian is given. The upper limit of this fauna is likewise recognized. So that it is not a question of fact but of nomenclature which is in dispute. With the modification of the accepted base-line at the top of the Tremadoc Slates, I shall continue to employ the terminology proposed by the illustrious author of the "Silurian System" as being quite adequate for the most recent requirements of investigation.[53]

§ 1. General Characters

Rocks.—The Silurian system consists usually of a massive series of graywackes, sandstones, grits, shales, or slates, with occasional bands of limestone. The arenaceous strata include pebbly grits and conglomerates, which are specially apt to occur at or near any local base of the formation, where they rest unconformably on older rocks. Occasional zones of massive conglomerate occur, as among the Llandovery rocks of Britain. The argillaceous strata are in some regions (Livonia, etc.) mere soft clays: most commonly they are hard fissile shales, but in some areas (Wales, etc.), where they have been subjected to intense compression, they appear as hard cleaved slates, or even as crystalline schists. In Europe, the limestones are, as a rule, lenticular, as in the examples of the Bala, Aymestry, and Dudley bands, though

[53] The reader who would peruse a weighty and dispassionate examination of this disputed question in geological nomenclature should turn to the essay by the venerable Prof. J. D. Dana on "Sedgwick and Murchison; Cambrian and Silurian" (Amer. Journ. Sci. xxxix. 1890, p. 167). With the conclusions of his examination of the whole question I most thoroughly agree.

in the basin of the Baltic some of the limestones have a greater continuity. In North America, on the other hand, the Trenton limestones in the Lower, and the Niagara limestone in the Upper Silurian division are among the most persistent formations of the eastern United States and Canada, while in the Western Territories vast masses of Silurian limestone constitute nearly the whole of the system. Easily recognizable bands in many Silurian tracts, especially in the northwest of Europe, are certain dark anthracitic shales or schists, which, though sometimes only a few feet thick, can be followed for many leagues. As they usually contain much decomposing iron-disulphide, which produces an efflorescence of alum, they are known in Scandinavia as the alum-slates. In Scotland, they are the chief repositories of the Silurian graptolites. Their black, coal-like aspect has led to much fruitless mining in them for coal. In the northern part of the State of New York, a series of beds of red marl with salt and gypsum occurs in the Upper Silurian series. In the Salt Range of the Punjab the group of saliferous strata occurs which has been already alluded to in the account of the Cambrian rocks. These salt-bearing deposits are the oldest yet discovered. In Styria and Bohemia, important beds of oolitic hæmatite and siderite are interstratified with the ordinary graywackes and shales. Occasionally sheets of various eruptive rocks (felsites, diabases, diorites, etc.) occur contemporaneously imbedded in the Silurian rocks (Wales, Lake District, S. Scotland, S.E. Ireland, etc.), and, with their associated tuffs, represent the volcanic ejections of the time.

As a rule, Silurian rocks have suffered from subsequent geological revolutions, so that they now appear inclined, folded, contorted, broken, and cleaved, sometimes even

metamorphosed into crystalline schists. In certain regions, however (Basin of the Baltic, New York, etc.), they still remain nearly in their original undisturbed positions.

LIFE.—The general aspect of the life of the Silurian period, so far as it has been preserved to us, may be gathered from the following summary published by Bigsby in 1868—plants 82 species; amorphozoa 136; foraminifera 25; cœlenterata 507; echinodermata 500; annelida 154; cirripeds 8; trilobita 1611; entomostraca 318; polyzoa 441; brachiopoda 1650; monomyaria 168; dimyaria 541; hetero-

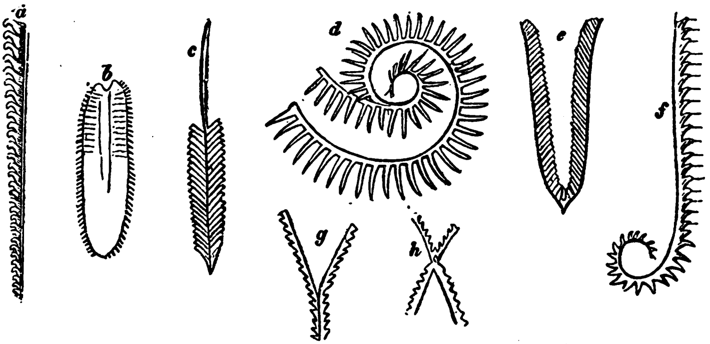

Fig. 340.—Group of Silurian Graptolites.

a, Monograptus priodon, Bronn (Wenlock); *b*, Phyllograptus typus, Hall (Lower Arenig); *c*, Diplograptus folium, His. (Llandovery); *d*, Rastrites peregrinus, Barr (Llandovery); *e*, Didymograptus Murchisoni, Beck. (Llandeilo); *f*, Monograptus Sedgwickii, Portl. (Llandovery); *g*, Dicranograptus ramosus, Hall (Llandeilo); *h*, Tetragraptus Hicksii, Hopk. (Lower Arenig).

poda 358; gasteropoda 895; cephalopoda 1454; pisces 37; class uncertain 12; total 8897 species. Barrande in 1872 published another census in which some variations are made in the proportions of this table, the total number of species being raised to 10,074, which has subsequently been still further increased.

The plants as yet recovered are chiefly fucoids. In many cases they occur as mere impressions, which are often probably not of vegetable origin at all, but casts of the trails

or burrows of worms, crustacea, etc.[54] Among the most abundant genera are Buthotrephis, Arthrophycus, Palæophycus, and Nematophycus (Carruth.). But in the Upper Silurian rocks beautifully preserved sea-weeds like the living Gelidium or Plocamium occur, such as the Chondrites verisimilis (Salt.) of the Ludlow rocks of Edinburghshire. Traces, however, of a higher vegetation have been discovered, which are of special interest as being the earliest known remains of a land-flora. Many years ago certain minute bodies (Pachytheca) in the Ludlow bone-bed were regarded as lycopodiaceous spore-cases, but some doubt has been cast on their organic grade. More recently, Dr. Hicks obtained from the Denbighshire grits of N. Wales other spores and likewise dichotomous stems, probably lycopodiaceous.[55] True lycopods (Sagenaria) have been met with in the Upper Silurian rocks of Bohemia. From the Clinton limestone of Ohio portion of a lepidodendroid tree (Glyptodendron eatonense) has been obtained. The Cincinnati group of strata, at the top of the Lower, and the Lower Helderberg at the top of the Upper Silurian formations of eastern North America, have yielded a microcosmical representation of the Carboniferous flora. The genera noted include Psilophyton, Calamophycus, Annularia, Protostigma, Sigillaria, and Sphenophyllum.[56] From the meagre evidence as yet collected, it would appear that the land of

[54] Nathorst, Kongl. Sensk. Vet. Akad. Handl. xviii. 1881, has imitated some of these markings by causing crustacea, annelids and mollusks to move over wet mud and gypsum, and has thus shown the high probability that they are not plants. (See Geol. Mag. 1882, pp. 22, 485; 1883, pp. 33, 192, 286.) Nathorst's opinion, adverse to the plant nature of the markings, is strongly opposed by Saporta in his "À propos des Algues Fossiles," 1882.

[55] Q. J. Geol. Soc. 1881, p. 482; 1882, pp. 97, 103.

[56] L. Lesquereux, Amer. Journ. Sci. (3) vii. p. 31; Proc. Amer. Phil. Soc. xvii. p. 63.

the Silurian period had a cryptogamic vegetation in which lycopods and ferns no doubt played the chief part.[57]

In the fauna of the Silurian rocks, the most lowly organisms known are foraminifera, of which several genera, including the still living genus Saccammina, have been detected. Certain layers of chert, widely spread over the south of Scotland, have yielded upward of a dozen genera with more than twenty species of radiolaria.[58] The Silurian seas possessed representatives both of the calcareous and of the siliceous sponges of modern times. Under the former group may be placed the genus Archæocyathus which occurs in the Cambrian system, and the genera Astræospongia and Amphispongia of the Upper Silurian rocks; under the latter group come Astylospongia and Protachilleum. Of the puzzling genera Receptaculites and Ischadites, the true relationships have not yet been determined. Nidulites, too, though a common fossil, is still a subject of uncertainty as to its organic grade, the latest view being that it may be related to the polyzoa.

Some of the most plentiful and characteristic denizens of the Silurian seas were undoubtedly the various hydrozoan genera united under the common name of graptolites (Fig. 340).[59] Among the monoprionidian forms, or those with a single row of cells, the genera Monograptus (of which upward of 40 species have been found in Britain), Rastrites and Cyrtograptus are characteristic of Upper Silurian rocks.

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[57] The student will find a valuable compendium of information by L. F. Ward regarding the fossil floras of past time all over the world in the 8th Ann. Rep. U. S. Geol. Surv. part ii. 1889.

[58] G. J. Hinde, Ann. Mag. Nat. Hist. 1890, p. 40.

[59] The student should consult Prof. Lapworth's Monograph "On the Geological Distribution of the Rhabdophora" (Ann. Mag. Nat. His. ser. 5, vols. iii. iv. v. and vi. 1879, 1880) in which the geological significance of the graptolites is fully discussed.

The diprionidian forms, or those with two rows of cells, are equally characteristic of the lower subdivision of the Silurian system, and are richest in genera, of which some of the commonest are Dicellograptus, Didymograptus, and Tetragraptus. Graptolites were formerly supposed to belong exclusively to Silurian rocks; but it has already been pointed out that they descend into the Cambrian system. Nevertheless it was in Silurian time that they reached their maximum development. A few genera (Diplograptus, Climacograptus, Retiolites) occur both in the Lower and Upper Silurian strata, though the species are not persistent. Through the researches chiefly of Prof. Lapworth it has been ascertained that the vertical range of the species of graptolites is comparatively limited, and hence that these fossils may be used to mark definite palæontological horizons. He enumerates twenty recognizable graptolite zones, one in the Upper Cambrian, eight in the Lower Silurian, and eleven in the Upper Silurian formations.[60] The peculiar form Stromatopora and several allied genera are now referred to the Hydrozoa.

Corals must have swarmed on those parts of the Silurian sea-floor on which calcareous accumulations gathered, for their remains are abundant among the limestones, particularly in the upper division of the system. Among the tabulate forms are the genera Favosites, so characteristic in the Upper Silurian limestones of Europe and America, Chætetes, Thecia, Halysites or chain coral, Syringopora, and Tetradium. The rugose corals are likewise abundant,

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[60] Op. cit. v. 1880, p. 197. O. Jaekel (Zeitsch. Deutsch. Geol. Ges. 1889, p. 653) has recently proposed to distinguish the monograptidæ in two groups, *Pristiograptus* characterizing the older and *Pomatograptus* the later parts of the Upper Silurian series.

some conspicuous genera being Stauria, Cyathaxonia, Cyathophyllum, Zaphrentis, Petraia, Omphyma, Strombodes, Ptychophyllum, and Acervularia (Fig. 345). The echinoderms were represented by star-fishes (Palæaster, Palæasterina, Palæocoma, Lepidaster), brittle-stars (Protaster, Eucladia), many forms of crinoids (Actinocrinus, Cyathocrinus, Glyptocrinus, Eucalyptocrinus, Taxocrinus, etc.), and particularly by species of cystideans (Echinosphærites, Sphæronites, Pleurocystites, Hemicosmites). The annelids of the Silurian sea-bottom comprised representatives of both the tubicolar and errant orders. To the former belong the genera Cornulites, Ortonia, Conchicolites, Serpulites, and also the still living genus Spirorbis. The errant forms are known chiefly by their burrows or trails, which appear in immense profusion on the surfaces of shales and sandstones (Arenicolites, Nereites, Scolithus, etc.), but also by their jaws, which occur in great numbers in the Wenlock and Ludlow rocks.[61]

The crustacea of the period have been abundantly preserved and form some of the most familiar and distinctive fossils of the system. Undoubted cirripeds have been found in the Silurian rocks of Britain, Bohemia, and North America (Turrilepas, Anatifopsis). Small ostracods abound in certain shales, some of the most frequent genera being Entomis, Beyrichia, Primitia, Leperditia, Aristozoe, Orozoe, Callizoe. The phyllopods, which, as we have seen, made their appearance in Cambrian times, continue to occur on scattered horizons, and generally not in great numbers, throughout the Lower and Upper Silurian rocks; characteristic genera are Caryocaris, Peltocaris, Dis-

[61] G. J. Hinde, Q. J. Geol. Soc. 1880, p. 368; Bihang. Svensk. Vet. Akad. Handl. vi. 1882.

cinocaris, Ceratiocaris, Dictyocaris, Cryptocaris, and Aptychopsis. But by far the most prolific order is that of the trilobites (Figs. 341, 345), which, beginning in the Cambrian, attained its maximum development in the Silurian, waned in the Devonian, and became extinct in the Carboniferous period. According to the census of Barrande in 1872 there were then 1579 known species, but this number has since been greatly increased. With a few exceptions the Cam-

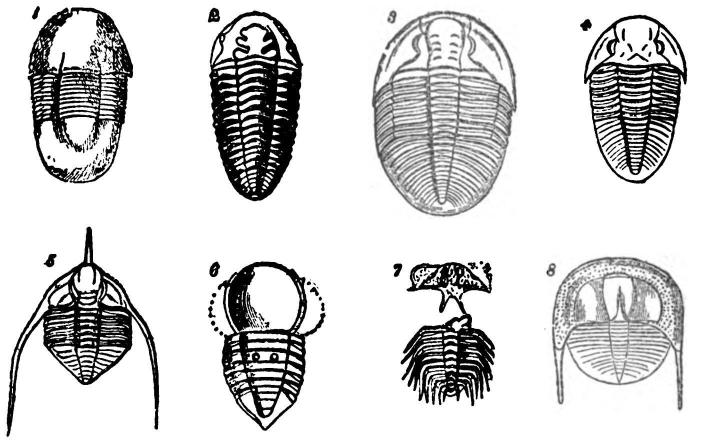

Fig. 341.—Group of Lower Silurian Trilobites.

1, Illænus Davisii, Salt. (½); 2, Calymene brevicapitata, Portl.; 3, Ogygia Buchii, Brongn. (½); 4, Asaphus tyrannus, Murch. (½): 5, Ampyx nudus, Murch. (½); 6, Æglina binodosa, Salt.; 7, Acidaspis Jamesii, Salt.; 8, Trinucleus Lloydii, Murch.

brian genera did not survive into Silurian time (p. 1218.) They were succeeded by many new genera which continued to live through most of the Silurian period. In the lower division of the system, characteristic genera are Æglina, Asaphus, Amphion, Ampyx, Barrandia, Chasmops, Cybele, Harpes, Ogygia, Placoparia, Remopleurides, and Trinucleus; some genera are common to both the lower and upper divisions (but usually with specific distinctions), such as Acidaspis,* Bronteus,* Calymene, Cheirurus, Cyphaspis,

Dalmanites, Encrinurus,* Homalonotus,* Illænus, Lichas, Phacops,*[62] and Sphærexochus. Proetus is confined to the upper division. Toward the top of the system eurypterids make their appearance, and continue to occupy a prominent place until the Carboniferous period. The Silurian genera are Pterygotus, Eurypterus, Slimonia, Stylonurus, and Hemiaspis.

The polyzoa of Silurian times have been tolerably well preserved, and present many peculiarities of structure. One

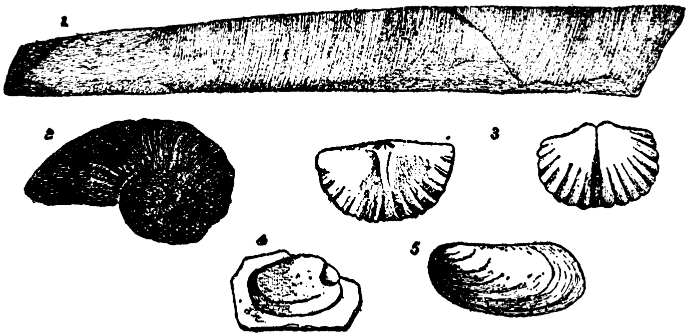

Fig. 342.—Group of Arenig Fossils.

1, Orthoceras cæreesiense, Hicks; 2, Bellerophon Ilanvirnensis, Hicks; 3, Orthis calligramma, Dalm. (enlarged); 4, Redonia anglica, Salt.; 5, Palæarca amygdalus, Salt.

of the most abundant genera is Fenestella, which ranges from Lower Silurian to Permian rocks; another, Ptilodictya, ascends into the Carboniferous system. Other genera are Retepora, Paleschara, and Hippothoa. So abundant are the brachiopods (many hundreds of species being known), and so characteristic on the whole are the species of them occurring in certain Silurian zones or bands, that these fossils must be regarded as of special value for purposes of stratigraphical comparison.[63] The old and still living

[62] Those genera marked with * are more characteristic of the Upper than of the Lower Silurian strata.

[63] For an account of the internal arrangements of some Silurian brachiopods

genera Discina, Lingula, and Crania are found on different horizons in the Silurian series. Characteristic types are **Acrotreta, Atrypa, Leptæna, Meristella, Orthis** (Figs. **342,**

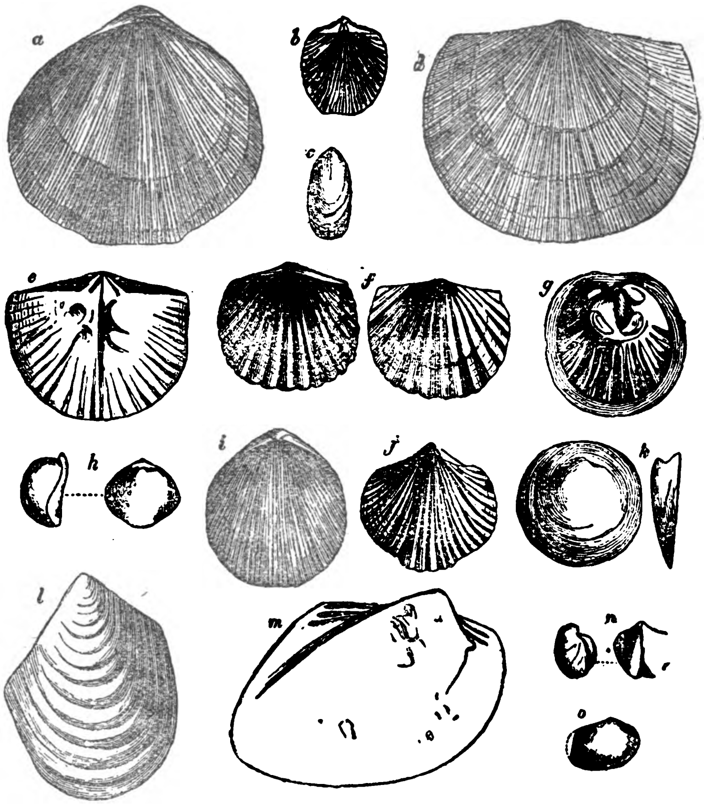

Fig. 343.—Group of Caradoc Fossils.

a, Porambonites intercedens, Pander; *b*, Orthis hirnantensis, McCoy; *c*, Lingula longissima, Pander (?); *d*, Strophomena grandis, Sby.; *e*, Orthis plicata, Sby.; *f*, Orthis calligramma, Dalm.; *g*, Crania divaricata, McCoy; *h*, Triplesia (?) maccoyana, Dav.; *i*, Atrypa (?) Headii, Billings (?); *j*, Atrypa marginalis, Dalm.; *k*, Discina oblongata, Portl.; *l*, Ambonychia prisca, Portl.; *m*, Palæarca billingsiana, Salt., *n*, Rhynchonella nana, Salt.; *o*, Cleidophorus ovalis, McCoy.

343), Pentamerus (Fig. 344), Porambonites, Rhynchonella (Fig. 346), Siphonotreta, Spirifer, Stricklandinia, Strophome-

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and a list of the Upper Silurian species of England, see Davidson, Geol. Mag. 1881, pp. 1, 100, 145, 239.

na (Fig. 346), and Triplesia. Some of these are particularly distinctive of certain zones. Thus, from the abundance of Pentameri in them, certain strata received the name of the "Pentamerus beds" (Fig. 344). Orthis is most abundant in species in the lower part of the Silurian system: Pentamerus, Rhynchonella, Spirifer, Chonetes and Terebratula occur in the upper. The lamellibranchs have been less abundantly preserved; some of their most frequent genera are the monomyarian Ambonychia (Fig. 343) and Pterinea and the dimyarian Ctenodonta, Modiolopsis, Goniophora, Orthonota (Fig. 346), Cleidophorus (Fig. 343), Palæarca, and Redonia (Fig. 342). Cardiola interrupta (Fig. 346) is a characteristic shell of the highest Upper Silurian rocks.

Of the gasteropods of the Silurian seas upward of 1300 species have been named; some of the more frequent genera are Acroculia, Cyclonema, Euomphalus (Fig. 346), Helicotoma, Holopæa, Holopella, Murchisonia, Ophileta, Platyschisma, Pleurotomaria, Raphistoma, Trochus (Fig. 346), and Subulites. Some heteropod forms occur, *e.g.* Bellerophon and Maclurea; but pteropods are more frequent, being represented sometimes abundantly by the genera Tentaculites (regarded by some as an annelid), Hyolithes (or Theca), Conularia, and Pterotheca. That the salt waters of the Silurian era swarmed with cephalopods may be inferred from the fact that according to Barrande's census no fewer than 1622 species had then been described. They are all tetrabranchiate. Some of the most abundant forms are straight shells, of which Orthoceras (Figs. 342, 346) is the type. This characteristically Palæozoic genus abounded in the Silurian period, when many of its individuals attained a great size. Barrande has described upward of 550 species from the basin of Bohemia. Of Cyrtoceras, in which

the shell was curved, the same small area has yielded more than 330 species. Phragmoceras (Fig. 346) likewise possessed a curved shell, but with an aperture contracted in the middle. In Ascoceras the shell was globular or flask-shaped, with curiously curved septa; in Lituites (Fig. 346) it was curled like that of Nautilus. The two latter genera occur in Silurian rocks, but while Lituites never outlived the Silurian period, Nautilus is still a living denizen of the sea.

The first traces of vertebrate life make their appearance in the Silurian system. They consist of the remains of fishes, the most determinable of which are the plates of placoderms (Pteraspis, Cephalaspis, Auchenaspis, Scaphaspis). The bone-bed of the Ludlow rocks has also yielded certain curved spines (Onchus), which have been referred to a cestraciont, and some shagreen-like plates which have been supposed to be scales of placoid fishes (Sphagodus, Thelodus), and bodies like jaws with teeth which were called Plectrodus, but which are now known to be lateral shield-spines of a cephalaspidean fish (Eukeraspis). It is probable that some of these remains have been incorrectly determined, and may belong to crustaceans or annelids. The Upper Silurian rocks have yielded, both in Europe and North America, great numbers of minute tooth-like bodies which were named "Conodonts" by their discoverer, Pander, and were supposed to be the teeth of such fishes as the lamprey, which possessed no other hard parts for preservation. These bodies have been also referred to different divisions of the invertebrata, but palæontologists now regard them as probably in most cases the jaws of annelids.[64]

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[64] Zittel and Rohon, Sitzb. Bayr. Akad. Munich, 1886, p. 108.

Satisfactory evidence of the occurrence of fishes in rocks of Silurian age is supplied by Mr. Walcott, who has described from the Lower Silurian rocks of Cañon City, Colorado, a number of fish remains, among which he has been able to identify dermal plates and scales belonging to genera like Asterolepis and Holoptychius, which play so important a part in the Devonian fauna.[65] According to Dr. J. V. Rohon, all the so-called "Conodonts" are not annelidian, but include undoubted teeth of fishes with recognizable dentine, enamel, and pulp-cavity. He describes from the Glauconite Sand of St. Petersburg forms belonging to two new genera named by him Palæodus and Archodus.[66]

Up to the present time no trace has been detected of any vertebrate land-animals of Silurian age. In Sweden, France, Scotland, and the United States, however, the discovery of remains of arachnid and insect life in Silurian rocks may herald the ultimate detection of higher forms of life. From the Upper Silurian strata of the island of Gothland a true scorpion has been discovered, which appears to differ in no essential respect from recent forms, except in the walking limbs, which are dumpy in form, and terminate in a single claw. One of the breathing stigmata on the second ventral scute shows clearly that the animal was an air-breather.[67] Subsequently a still more perfect example of the same genus (Palæophoneus) was described from the Upper Silurian rocks of Lesmahagow, Lanarkshire (Fig. 347). The presence of a poison-gland and sting at the extremity of the tail shows that, like their modern representatives, these ancient animals

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[65] Bull. Geol. Soc. America, iii. 1892, p. 153.

[66] J. V. Rohon, Bull. Acad. Imp. Sci. St. Petersbourg, xxxiii. 1890, p. 269.

[67] G. Lindström, Comptes Rend. xcix. 1884; T. Thorell and G. Lindström, K. Svensk. Vet. Akad. Handl. xxi. No. 9, 1885.

preyed on other denizens of the land. Soon after the European discoveries, the finding of a scorpion in the "Water-lime" (Upper Silurian) of New York was announced.[68] These specimens lifted the veil that had concealed from us all evidence of the terrestrial fauna of this ancient period of geological history. If there were scorpions on the land, there were almost certainly other land-animals on which they lived. Mr. Peach has suggested that they may have fed partly on marine crustacean eggs left bare by the tides.[69] But that insects already existed has been made known by the discovery of a true insect-wing in the Lower Silurian (probably Caradoc) sandstone of Jurques, Calvados.[70] It measures about 1⅜ inch long, and is distinguished by the length of the anal nervure and the small breadth of the axillary area. It is a primeval of Blatta, and has been named by M. Brongniart Palæoblattina. We may be confident that these are not the only relics of the Silurian terrestrial fauna that have been preserved, and we may hope that still more remarkable treasures are yet to be unearthed from their primeval resting-places.

§ 2. Local Development

Britain.[71]—In the typical area where Murchison's discoveries were first made, he found the Silurian rocks divisible into two great and well-marked series, which he termed Lower and Upper. This classification has been found to hold good over a large part of the world. The subjoined

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[68] R. P. Whitfield, Science, vi. 1885, p. 87.
[69] B. N. Peach, Nature, xxxv. 1885, p. 295; Trans. Roy. Soc. Edin. xxx. 1882.
[70] Ch. Brongniart, Comptes Rend. xcix. 1884, p. 1164; Geol. Mag. 1885, p. 481.
[71] See Murchison's "Silurian System," and "Siluria"; Sedgwick's "Synopsis," cited p. 1210; Ramsay's "North Wales" in Memoirs of Geol. Surv. vol. iii.; Etheridge, Address, Q. J. Geol. Soc. 1881; numerous local memoirs in recent volumes of the Q. J. Geol. Soc. and Geol. Mag., particularly by Hicks, Ward, Hughes, Keeping, Lapworth, etc.

table shows the arrangement and nomenclature of the various subdivisions of the Silurian system:

			Feet.
Upper Silurian.	6. Ludlow group .	approximate average thickness	1900
	5. Wenlock group .	"	1600
	4. Llandovery group	"	3000
Lower Silurian.	3. Bala and Caradoc group	"	6000
	2. Llandeilo group .	"	3000
	1. Arenig group .	"	4000
			19,500

a. Lower Silurian

The typical subdivisions in Wales and Shropshire will first be described, and afterward the development of the series in other parts of Britain.

1. Arenig Group.—These rocks consist of dark slates, shales, flags, and bands of sandstone. They are abundantly developed in the Arenig Mountain, where, as originally described by Sedgwick, they include masses of associated volcanic rocks. In their abundant suite of organic remains new genera of trilobites make their appearance (Æglina, Barrandia, Calymene, Homalonotus, Illænopsis, Illænus, Phacops, Placoparia, Trinucleus). Pteropods are represented by species of Conularia and Theca; brachiopods by Lingula, Lingulella, Obolella, Discina, Siphonotreta, and Orthis; lamellibranchs by Palæarca and Ribeiria; gasteropods by Ophileta and Pleurotomaria; heteropods by Bellerophon and Maclurea; and cephalopods by Orthoceras. But the most abundant organisms are the graptolites, of which no fewer than twenty genera have been found in the Arenig rocks of Britain. In the lower part of the group the genus Tetragraptus is especially characteristic, for it is not at present known to occur on any higher or lower horizon. Here lies the lowest Silurian graptolitic zone, that of Tetragraptus bryonoides. The genera Loganograptus, Clonograptus, Schizograptus, and Dichograptus are probably also peculiar to the same strata, as well as the species Didymograptus extensus, D. pennatulus, and the only known examples of Retiograptus. The upper part of the Arenig group (zone of Didymograptus bifidus) is especially marked by the presence of Phyllograptus, in association with forms of Dichograptus like D. bifidus. Species peculiar to it, besides the last-named, are D. minutus and some forms of Diplograpta, such as Climacograptus confertus.[72]

Dr. Hicks has proposed to construct a separate group

[72] Lapworth, Ann. Mag. Nat. Hist. vol. vi. 1880, p. 197.

under the name of "Llanvirn," by taking the upper part of the Arenig and lower portion of the Llandeilo rocks, making a total thickness of about 2000 feet of strata near St. David's in South Wales.[73] It is in this group of strata that the trilobites Acidaspis, Barrandia, Illænus, and Phacops make their earliest appearance. Sir A. C. Ramsay believed that in North Wales there is an unconformable overlap of the Arenig upon the Tremadoc and older beds; but in South Wales there does not appear to be any break.[74]

A remarkable feature in the history of the Arenig rocks in Wales was the volcanic action during their formation, whereby various felsitic or rhyolitic lavas, with abundant discharges of fine ashes and coarser agglomerates, were erupted over the sea-bottom and interstratified with the contemporaneously deposited sediments, while more basic sills were subsequently injected under the volcanic sheets. Some of the more important Welsh mountains consist mainly of these ancient volcanic materials—Cader Idris, the Arans, Arenig Mountain, and others.[75]

2. Llandeilo Group.—These dark argillaceous and occasionally calcareous flagstones, sandstones, and shales were first described by Murchison as occurring at Llandeilo, in Carmarthenshire. They reappear near St. David's, on the coast of Pembrokeshire, and at Builth, in Radnorshire. In the lower subdivision of them a seam of limestone occurs, while intercalated igneous rocks are specially noticeable in the upper subdivision. It was at one time believed that graptolites were almost confined to this group. These fossils, now known to range from the Cambrian to the top of the Silurian system, occur abundantly in the Llandeilo rocks, and present there a transitional character between the Arenig types below and those in the Caradoc or Bala rocks above. In the lower portions of the group the most abundant genus is Didymograptus, D. Murchisoni being the characteristic species (and serving to mark a graptolitic zone) accompanied by many of the Arenig species, together with new forms of Cryptograptus and Glossograptus. In the middle part of the group the D. Murchisoni becomes very rare and is associated with Diplograptus foliaceus and Cli-

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[73] Pop. Science Rev. 1881, p. 289.

[74] "Geology of N. Wales," Mem. Geol. Surv. iii.

[75] For descriptions of the Arenig lavas and tuffs consult the "Geology of N. Wales" already cited; also G. A. Cole and C. V. Jennings, Quart. Journ. Geol. Soc. xlv. 1889. Geol. Mag. 1890, p. 447; Jennings and G. J. Williams, Quart. Journ. Geol. Soc. xlvii. 1891, p. 374. Op. cit. Presidential Address, p. 165.

macograptus Scharenbergi. In the Upper Llandeilo rocks graptolites of the type of Cryptograptus tricornis and Climacograptus Scharenbergi are abundant, also species of Cœnograptus with Dicellograptus sectans (zone of Cœnograptus gracilis). Trilobites are characteristic fossils of the group, upward of fifty species belonging to eighteen or twenty genera being known. These include characteristic forms which do not range beyond the group, Asaphus tyrannus, Calymene cambrensis, Trinucleus Lloydii, and T. favus being found in the lower subdivision, and Barrandia Cordai, Cheirurus Sedgwickii, and Ogygia Buchii in the upper. The phyllopod Peltocaris aptychoides is also peculiar. The brachiopods include the genera Acrotreta, Crania, Discina, Leptæna, Lingula, Orthis, Rhynchonella, and Strophomena, some of which here make their first appearance. The lamellibranchs are represented by species of Cardiola (C. interrupta) and Modiolopsis (M. expansa, M. inflata), the gasteropods by Cyclonema, Euomphalus, Murchisonia, Pleurotomaria, Raphistoma, and Turbo, the heteropods by Bellerophon, Ecculiomphalus, and Maclurea, the pteropods by Conularia and Theca, the cephalopods by Cyrtoceras, Orthoceras, and Endoceras.

3. Caradoc and Bala Group.—Under this name were placed by Murchison the thick yellowish and gray sandstones of Caer Caradoc in Shropshire, and the Horderley and May Hill Sandstone. It was afterward ascertained that the gray and dark slates, grits, and sandstones, described by Sedgwick as occurring round Bala in Merionethshire and regarded by him as the higher part of his Cambrian system, were really slightly different lithological developments of the same stratigraphical division. In the Shropshire area, some of the rocks are so shelly as to become strongly calcareous. In the Bala district, the strata contain two limestones separated by a sandy and slaty group of rocks 1400 feet thick. The lower or Bala limestone (25 feet thick) has been traced as a variable band over a large area in North Wales. It is usually identified with the Coniston limestone of the Westmoreland region. The upper or Hirnant limestone (10 feet) is more local. Bands of volcanic tuffs and large beds of various felsitic lavas occur among the Bala beds, and prove the contemporaneous ejection of volcanic products. These attain a thickness of several thousand feet in the Snowdon region.[76]

[76] For accounts of the volcanic phenomena of the Caradoc-Bala series of Wales, see A. C. Ramsay's "Geology of North Wales," forming vol. iii. of the

A large suite of fossils has been obtained from this group. The sponges are represented by Sphærospongia, Acanthospongia, and other genera. The graptolites are strongly differentiated from those of the Arenig rocks by the entire absence of Dichograptidæ and Phyllograptidæ. The Diplograptidæ, feebly represented in the Arenig and Lower Llandeilo groups, are now, as Prof. Lapworth points out, the dominant forms, occurring in swarms in every zone. The two genera Diplograptus and Climacograptus are especially abundant. The following successive zones, each marked by the prevalence of its own species of graptolite, have been observed by Prof. Lapworth in ascending order: (1) Zone of Climacograptus Wilsoni, (2) Zone of Dicranograptus Clingani, (3) Zone of Pleurograptus linearis, (4) Zone of Dicellograptus complanatus, (5) Zone of Dicellograptus anceps. The same observer remarks upon the extraordinary extinction of families, genera, and species of graptolites during the period of the Caradoc-Bala rocks. "The entire families of the Dicranograptidæ, Leptograptidæ, and Lasiograptidæ, disappear from sight altogether. The only families that survive into the Llandovery rocks are those of the Diplograptidæ and Retiolitidæ, and these only in a very degenerate form." Yet it is remarkable that it was during Caradoc time that the Dicranograptidæ and Leptograptidæ attained their highest development.[77]

To the conditions that allowed the deposition of limestone bands in this group we doubtless owe the presence of upward of 40 species of corals (Fig. 345) belonging to Alveolites, Cyathophyllum, Favosites, Halysites, Heliolites, Monticulipora, Omphyma, Petraia, etc. The echinoderms are represented by encrinites of the genera Actinocrinus, Cyathocrinus, and Glyptocrinus, by no fewer than 16 species of cystideans (Echinosphærites, Sphæronites, Agelacrinites, Hemicosmites, etc.), and by star-fishes of the genera Palæaster, Protaster, and Stenaster; the annelids by Serpulites, and numerous burrows and tracks; the trilobites by species of Acidaspis (7 species), Ampyx (6), Asaphus (6), Calymene (5), Cheirurus (6), Cybele (2), Encrinurus (3), Homalonotus (4), Illænus (9), Lichas (5), Phacops (15), Remopleurides

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General Memoirs of the Geological Survey; Harker's "Bala Volcanic Series of Caernarvonshire," being the Sedgwick Prize Essay for 1888; F. Rutley, Quart. Journ. Geol. Soc. xxxv. 1879, p. 508; W. W. Watts, op. cit. xli. 1885, p. 532; and vol. xlvii. 1891, Presidential Address, p. 117.

[77] Lapworth, Ann. Mag. Nat. Hist. v. 1880, p. 358 *et seq.*

(7), Trinucleus (6); the ostracods by Beyrichia, Leperditia, Cythere, Primitia, and Entomis; the polyzoa by Fenestella, Glauconome, Ptilodictya, and Retepora; the brachiopods by Atrypa, Rhynchonella, Meristella, Leptæna (10 species), Orthis (nearly 40), Strophomena (17), Crania, Discina, and Lingula; the lamellibranchs by Ctenodonta (17 species), Orthonota (5), Modiolopsis (15), Pterinea (6), Ambonychia (8), Palæarca (5); the gasteropods by Murchisonia, Pleurotomaria, Raphistoma, Cyclonema, Euomphalus, Holopæa and Holopella; the pteropods by Tentaculites, Conularia, Theca; the heteropods by species of Bellerophon, Ecculiomphalus and Maclurea; and the cephalopods by the genera Orthoceras (between 30 and 40 species), Cyrtoceras, Lituites, etc.

The Lower Silurian rocks, typically developed in Wales, extend over much of Britain, though largely buried under more recent formations. They rise into the hilly tracts of Westmoreland and Cumberland,[78] where they consist of the following subdivisions in descending order:

Coniston Limestone series with the Ashgill shales above the limestone and the Dufton shales below it .	=	Bala beds.
Borrowdale volcanic series (green slates and porphyries): tuffs and lavas without ordinary sedimentary strata except at base, 12,000 ft.	=	Part of Bala, whole of Llandeilo, and perhaps part of Arenig groups.
Skiddaw Slates, 10,000 or 12,000 ft., base not seen	=	Arenig group, with perhaps Tremadoc slates and Lingula Flags.

Apart from the massive intercalation of volcanic rocks, these strata present considerable lithological and palæontological differences from the typical subdivisions in Wales. The Skiddaw slates are black or dark-gray, argillaceous, and in some beds sandy rocks, often much cleaved, though seldom yielding workable slates, sometimes soft and black, like Carboniferous shale. As a rule, they are singularly unfossiliferous, but in some of their less cleaved and altered portions they have yielded about 40 species of graptolites; Lingula brevis, traces of annelids, a few trilobites (Æglina, Agnostus, Asaphus, etc.), some phyllopods (Caryocaris), and remains of plants (?) (Buthotrephis, etc.). According to Pro-

[78] Sedgwick's "Three Letters addressed to W. Wordsworth," 1843; J. C. Ward, "Geology of the North Part of the English Lake District" (Geological Survey Memoir) 1876; Nicholson, "Essay on the Geology of Cumberland and Westmoreland," 1868. See also papers by Harkness, Nicholson, Hughes, Marr and others in Q. J. Geol. Soc. and Geol. Mag.

fessors Nicholson and Lapworth, they may be provisionally divided into two groups, the lower consisting of dark flagstones and shales, distinguished by species of Tetragraptus, Didymograptus, Phyllograptus, Diplograptus, Loganograptus, Temnograptus, Schizograptus, Ctenograptus, Dichograptus, and the upper made up of black shales and mudstones, containing some of the same and some different species of Didymograptus and Phyllograptus, and species of Trigonograptus, Trichograptus, Glossograptus, Diplograptus, and Climacograptus. The Skiddaw slates have been invaded by granite and other eruptive rocks, and display around these a well-marked contact-metamorphism (p. 1003).

Toward the close of the long period represented by the Skiddaw slates, volcanic action manifested itself, first by intermittent showers of ashes and streams of lava, which were interstratified with the ordinary marine sediment, and then by a more powerful and continuous series of explosions, whereby a huge volcanic mountain or group of cones was piled up above the sea-level. The vast pile of volcanic material (estimated at some 12,000 feet in total thickness) consists entirely of lavas and ashes without the interstratification of ordinary sediment except at the base and the top. The lower lavas are varieties of andesite, which are also met with in the central and higher parts of the Borrowdale volcanic series, while rhyolitic felsites were specially poured out toward the close of the volcanic period. Enormous quantities of fine volcanic ashes were likewise discharged. These various volcanic rocks form the picturesque hills of the Lake District.[79] The length of time occupied by this volcanic episode in Cambrian geology may be inferred from the fact that all the Llandeilo and a large part of the Bala beds are absent here. The volcanic island slowly sank into a sea wherein Bala organisms flourished. In some places a group of shales occasionally 300 feet thick, and known as the Dufton shales, overlies the Borrowdale series, and contains among other characteristic species Strophomena expansa, Leptæna sericea, Trinucleus concentricus, Homalonotus bisulcatus, Illænus Bowmanni. The most marked rock of the overlying series is the Coniston limestone, which

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[79] On the volcanic geology of this region consult J. C. Ward in the work above cited; Presidential Address to Geological Society, Quart. Journ. Geol. Soc. 1891, p. 137, and authors there given.

has yielded such familiar Bala species as Favosites fibrosa, Heliolites interstinctus, Cybele verrucosa, Leptæna sericea, Orthis Actoniæ, O. biforata, O. calligramma, O. elegantula, O. porcata, and Strophomena rhomboidalis. These organisms and their associates, gathering on the submerged flanks of the sinking volcano, before the eruptions had finally ceased, formed there the bed of limestone which is now traceable for many miles through the Westmoreland hills, like the Bala limestone of North Wales, which it probably represents. This Coniston limestone has an overlying conformable group of argillaceous strata (Ashgill shales) containing Trinucleus concentricus, Phacops apiculatus, P. mucronatus, Strophomena siluriana, and other Lower Silurian fossils. Not far to the east, at the base of the great Pennine escarpment, contemporaneous volcanic rocks in the Coniston series are well developed.[80] But the enormous volcanic group of Westmoreland and Cumberland dies out rapidly in that direction, for in the Craven district it is represented by a series of sandstones, grits and slates (often green), probably 10,000 feet thick, which passes up conformably into the Coniston limestone series.[81]

The Southern Uplands of Scotland are formed almost wholly of Lower and Upper Silurian strata which have been thrown into innumerable plications, often overthrust and reversed. The working out of this complicated structure has been made possible chiefly by the evidence furnished by certain zones of graptolitic shales, as has been well worked out by Prof. Lapworth. The following table exhibits in descending order the subdivisions which have been established, with some of their characteristic fossils.[82]

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[80] Harkness, Q. J. Geol. Soc. xxi. 1865, p. 235. Nicholson, Geol. Mag. 1869, p. 213. This "Crossfell inlier" has been described by Messrs. Nicholson, Marr and Harker, Quart. Journ. Geol. Soc. xlvii. 1891, p. 500.

[81] Hughes, Geol. Mag. iv. 1867, p. 346. This area had previously been described by Sedgwick, Trans. Geol. Soc. (2) iii. p. 1; and by Phillips, Q. J. Geol. Soc. viii. p. 35.

[82] See Lapworth, Geol. Mag. 1889, pp. 20, 59. The prolongation of the remarkable volcanic zone over the greater part of the Southern Uplands has been detected by Mr. B. N. Peach in the course of the Geological Survey.

	Leadhills and N.E. part of region	Moffat and central part of region	Ayrshire and S.W. part of region
Caradoc or Bala	Pale sandy shales and flagstones with occasional bands of grit and seams of black shale with Upper Hartfell graptolites (Lowther Shales).	Green and gray mudstones with black shales, forming the Upper Hartfell Shales and divided into: 3. Zone of Dicellograptus anceps, Diplograptus truncatus, Climacograptus scalaris. 2. Mudstone (unfossiliferous). 1. Zone of Dicellograptus complanatus, Dictyonema moffatensis.	Green mudstones and shales (Drummuck) with Staurocephalus globiceps, Trinucleus, Asaphus, Dicellograptus anceps, Diplograptus truncatus. Gray and dark flagstones and shales (Whitehouse) with Ampyx, Asaphus, Dicellograptus complanatus, Diplograptus socialis, D. foliaceus, D. quadrimucronatus, Leptograptus flaccidus, Climacograptus tubuliferus.
	Graywackes and shales passing north-eastward into a thick group in which the Lower Hartfell black graptolitic shale loses its lithological character. The graywackes are often pebbly, and contain some thin limestone (Wrae, Winkstone) with Caradoc fossils.	Band of black shales about 50 feet thick forming the Lower Hartfell Shales and containing the following zones: 3. Zone of Pleurograptus linearis, with Leptograptus flaccidus, Diplograptus foliaceus, Climacograptus tubuliferus. 2. Zone of Dicranograptus Clingani, with D. ramosus, Climacograptus caudatus, C. bicornis, Dicellograptus Forchhammeri. 1. Zone of Climacograptus Wilsoni, with Cryptograptus tricornis, Diplograptus, rugosus, Lasiograptus Harknessi, Climacograptus Scharenbergi.	Flags, shales, and grits (Ardwell) with Dicellograptus, Forchhammeri, Dicranograptus ramosus, Climacograptus caudatus, C. Scharenbergi, Cryptograptus tricornis, Diplograptus rugosus, Lasiograptus Harknessi.
Llandeilo	Graywackes and shales, including the Glenkiln Black Shales with their distinctive graptolites and bands of red nodular chert, with courses of red and green mudstone, massive gray and black cherts and occasional black shales containing Upper Llandeilo graptolites.	Group of grits and green shales with black and gray cherts and several bands of black graptolitic shale forming the Glenkiln Shales. The cherts contain more than 20 species of radiolaria. The black (Glenkiln) shales are marked by the occurrence of Didymograptus superstes, Cœnograptus gracilis, Dicellograptus sextans, D. divaricatus, Diplograptus mucronatus, and other forms.	Grits, flags, and shales (Balclatchie) with Dicranograptus rectus, Glossograptus Hicksii, Climacograptus tricornis, etc. Massive conglomerate with pebbles from the cherts and volcanic group below (Girvan). Shales, with Didymograptus superstes, Dicellograptus sextans, Diplograptus euglyphus, Clathrograptus. Limestone (Stinchar, Craighead) with Maclurea Logani, Ophileta compacta, Leptæna sericea, and many other Llandeilo-Caradoc fossils. Thick conglomerate with some sandstones containing Orthis confinis, etc. Red and green mudstones with nodules and bands of red chert and jasper containing radiolaria.
	Slaggy diabases, tuffs, and agglomerates only seen on the crests of the anticlines where revealed by denudation.	Fine tuffs or volcanic mudstones are generally the only indications of the volcanic group in this district. But much of the material of the ordinary graywackes and shales has probably been derived from the denudation of the volcanic rocks.	Volcanic group, slaggy diabases and porphyrites with breccias and agglomerates and traversed by gabbros, serpentines, and other intrusive rocks (Ballantrae and lower part of Stinchar valley).
Arenig	Not seen.	Not seen.	Black shales and limestones (Ballantrae, Lendalfoot) with Phyllograptus typus, Tetragraptus bryonoides, T. quadribrachiatus, Didymograptus extensus, D. bifidus, etc., and forms of Dictyonema, Lingula and Obolella.

In the northeast of Ireland a broad belt of Silurian rocks, crossing from the southwest of Scotland, runs from the coast of Down into the heart of the counties of Roscommon and Longford. It is marked by the same graptolitic zones that occur in Scotland. The Glenkiln shales with their typical Llandeilo graptolites are found to the south of Belfast Lough, while the Hartfell shales with their Caradoc fossils have also been observed.[83] The richest fossiliferous localities among the Irish Silurian rocks are found at the Chair of Kildare, Portrane near Dublin, Pomeroy in Tyrone, and Lisbellan in Fermanagh, where small protusions of the older rocks rise as oases among the surrounding later formations. Portlock brought the northern and western localities to light, and Murchison pointed out that, while a number of the trilobites (Trinucleus, Phacops, Calymene, Illænus), as well as the simple plated Orthidæ, Leptænæ, and Strophomenæ, some spiral shells, and many Orthocerata, are specifically identical with those from the typical Caradoc and Bala beds of Shropshire and Wales, yet they are associated with peculiar forms, first discovered in Ireland, and very rare elsewhere in the British Islands. Among these distinctive fossils he cited the trilobites, Remopleurides, Harpes, Amphion, and Bronteus, with smooth forms of Asaphus (Isotelus), which, though abundant in Ireland and America, had seldom been found in Wales or England, and never on the continent.[84] In the southeast of Ireland a large tract of Silurian rocks extends through the counties of Wicklow, Wexford, and Waterford. In this area also the Llandeilo and Caradoc graptolitic zones occur. Even as far south as the southern coast-line of Waterford black shales continue the physical aspect of the Glenkiln shales, and contain some of the same graptolites. We have thus evidence that the black carbonaceous mud in which these graptolites lived spread over the sea-floor for a distance of at least 300 miles.

b. Upper Silurian

Wales and Shropshire.—This series of rocks occurs in two very distinct lithological types in the British Islands.

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[83] W. Swanston, Trans. Belfast Nat. Field Club, 1876–77. Lapworth, Ann. Mag. Nat. Hist. iv. 1879, p. 424.

[84] "Siluria," p. 174. The upper portion of the Pomeroy section has yielded Llandovery graptolites, so that the strata there are partly Lower and partly Upper Silurian.

So great indeed is the contrast between these types, that it is only by a comparison of organic remains that the whole has been grouped together as the deposits of one geological period. In the original Shropshire region described by Murchison, and from which his type of the system was taken, the strata are comparatively flat, soft, and unaltered, consisting mainly of somewhat incoherent sandy mudstone and shale, with occasional bands of limestone. But as these rocks are followed into North Wales, they are found to swell out into a vast series of grits and shales, so like portions of the hard altered Lower Silurian rocks that, save for the evidence of fossils, they would naturally be grouped as part of that more ancient series. In Westmoreland and Cumberland, and still further north in the border counties of Scotland, also in the southwest of Ireland, it is the North Welsh type which prevails. This type, therefore, is really the prevalent one in Britain, extending over many hundreds of square miles, while the original Shropshire type hardly spreads beyond the border district between England and Wales.

Taking first the original tract of Siluria (W. England and E. and S.E. Wales), we find a decided unconformability separating the Lower from the Upper Silurian deposits. In some places the latter steal across the edges of the former, group after group, till they lie directly upon the Cambrian rocks. Indeed, in one district, between the Longmynd and Wenlock Edge, the base of the Upper Silurian rocks is found within a few miles to pass from the Caradoc group across to the Longmyndian rocks. It is evident, therefore, that in the Welsh region very great disturbance and extensive denudation preceded the commencement of the deposition of the Upper Silurian rocks. As Sir A. C. Ramsay has pointed out, the area of Wales, previously covered by a wide though shallow sea, was ridged up into a series of islands, round the margin of which the conglomerates at the base of the Upper Silurian series began to be laid down. This took place during a time of submergence, for these conglomeratic and sandy strata are found creeping up the slopes and even capping some of the hills, as at Bogmine, where they reach a height of 1150 feet above the sea. The subsidence probably continued during the whole of the interval occupied by the deposition of the Upper Silurian strata, which were thus piled to a depth of from 3000 to 5000 feet over the disturbed and denuded platform of Lower Silurian rocks.

Arranged in tabular form, the subdivisions of the Upper Silurian rocks of Wales and the adjoining counties of England are in descending order as follows:

	Base of Old Red Sandstone.	
3. Ludlow group.	Tilestones. Downton Castle Sandstone, 90 feet. Ledbury Shales, 270 feet. Upper Ludlow Rock, 140 feet. Aymestry Limestone, up to 30 or 40 feet. Lower Ludlow Rock, 350 to 700 feet.	
2. Wenlock group.	Wenlock or Dudley Limestone, 300 feet Wenlock Shale, up to 2300 feet . . . Woolhope or Barr Limestone and Shale, 150 feet	— Denbighshire Grits of North Wales.
1. Llandovery group.	Tarannon Shales, 1000 to 1500 feet. Upper Llandovery Rocks and May Hill Sandstone, 800 feet. Lower Llandovery Rocks, 600 to 1500 feet.	

1. Llandovery Group.—The most marked lithological character of this group in Britain is the occurrence of conglomerates which indicate the terrestrial disturbance and extensive denudation that followed the close of the deposition of the Lower Silurian rocks.

(*a*) *Lower Llandovery.*—In North Wales, the Bala beds, about five miles S.E. of Bala Lake, begin to be covered with gray grits, which gradually expand southward until they attain a thickness of 1000 or even 1500 feet. These overlying rocks are well displayed near the town of Llandovery, where they contain some conglomerate bands, and where Mr. Aveline detected an unconformability between them and the Bala group below them. Elsewhere they seem to graduate downward conformably into that group. They cover a considerable breadth of country in Cardigan and Carmarthenshire, owing to the numerous undulations into which they have been thrown, and they extend as far as Haverford West in Pembrokeshire. A marked change is now visible in the fossil contents of the rocks, as compared with those of the Lower Silurian subdivisions. Thus the familiar Lower Silurian types of trilobites become few or extinct, such as Agnostus, Ampyx, Asaphus, Ogygia, Remopleurides, Trinucleus, and their places are taken by species of Acidaspis, Encrinurus, Phacops, Proëtus, and other genera. A still more striking contrast occurs among the types of graptolites. The families of the Dicranograptidæ, Leptograptidæ, and Lasiograptidæ wholly disappear, and the forms which now take their place and distinguish the Upper Silurian rocks belong to the Monograptidæ

which gradually exclude the Dioplograptidæ, until before the higher parts of the system are reached they are the sole representatives of the graptolites. Four graptolitic zones have been recognized in the Llandovery group, viz. in ascending order: (1) Diplograptus acuminatus, (2) Dioplograptus vesiculosus, (3) Monograptus gregarius, (4) Monograptus spinigerus. Besides these species, Monograptus tenuis, M. attenuatus, M. Hisingeri, M. lobiferus, and Rastritus peregrinus are common Llandovery forms. Other characteristic fossils are Orthis elegantula, Stricklandinia (Pentamerus) lens, Meristella crassa, and Calymene Blumenbachii. From the abundance of the peculiar brachiopods termed Pentamerus in the Lower, but still more in the Upper Llandovery rocks, these strata were formerly grouped together under the name of "Pentamerus beds." Though the same species are found in both divisions Pentamerus oblongus is chiefly characteristic of the upper group and comparatively infrequent in the lower, while Stricklandinia (Pentamerus) lens abounds in the lower, but appears more sparingly in the upper. The genus ascends into the Wenlock and Ludlow groups, and is specially distinctive of Upper Silurian rocks.

(*b*) *Upper Llandovery and May Hill Sandstone.*—This subgroup has received the name of May Hill Sandstone from the locality in Gloucestershire where, as first shown by Murchison, it is well displayed. Sedgwick pointed out that it forms over a wide region the natural base to the Upper Silurian series, for it rests unconformably on all older rocks. It consists of gray, yellow and brown ferruginous sandstones and conglomerates, sometimes calcareous from the abundance of shells, which are apt to weather out and leave casts. Where the organisms have been most crowded together, the rock even passes into a limestone (Pentamerus limestone, Norbury limestone, Hollies limestone). The lower members are usually strongly conglomeratic, the pebbles being derived, sometimes in great part, from Lower Silurian rocks. Appearing on the coast of Pembrokeshire at Marlos Bay, this sub-group ranges across South Wales until it is overlapped by the Old Red Sandstone. It emerges again in Carmarthenshire, and trends northeastward as a narrow strip at the base of the Upper Silurian series, from a few feet to 1000 feet or more in thickness, as far as the Longmynd, where, as a marked conglomerate wrapping round that ancient Cambrian ridge, it disappears. In the course of this long tract it passes successively and uncon-

formably over Lower Llandovery, Caradoc, Llandeilo, Cambrian, and pre-Cambrian rocks.

Among the fossils are some traces of fucoids: sponges (Cliona, a burrowing form like the modern Cliona); species of Monograptus (M. Hisingeri, M. intermedius, M. crenularis), Rastrites (R. peregrinus), Diplograptus (D. Hughesi), Cephalograptus (C. cometa); a number of corals (Petraia, Heliolites, Favosites, Halysites, Syringopora, etc.); a few crinoids and the earliest known sea-urchins (Palæchinus); the genus Tentaculites is particularly abundant; a number of trilobites, of which Phacops Stokesii, P. Weaveri, Encrinurus punctatus, Calymene Blumenbachii, Proëtus Stokesii, and Illænus Thomsoni are common; numerous brachiopods, as Atrypa hemispherica, A. reticularis, Pentamerus oblongus, Stricklandinia lyrata, S. lens, Leptæna transversalis, Orthis calligramma, O. elegantula, O. reversa, Strophomena compressa, S. pecten, and Lingula parallela; lamellibranchs of the mytiloid genera Orthonota, Mytilus, and Modiolopsis, with forms of Pterinea, Ctenodonta, and Lyrodesma; gasteropods, particularly the genera Acroculia, Raphistoma, Murchisonia, Pleurotomaria, Cyclonema, Holopella; heteropods, especially the species Bellerophon dilatatus, B. trilobatus, and B. carinatus; and cephalopods, chiefly Orthocerata, with some forms of Actinoceras, Cyrtoceras, Tretoceras, and Phragmoceras, and the old species Lituites cornu-arietis.

(c) *Tarannon Shale.*—Above the Upper Llandovery beds comes a very persistent band of fine, smooth, light gray or blue slates, which has been traced from the mouth of the Conway into Carmarthenshire. These strata, termed the "paste-rock" by Sedgwick, have an extreme thickness of 1000 to 1500 feet. Poor in organic remains, their chief interest lies in the fact that the persistence of so thick a band of rock between what were supposed to be continuous and conformable formations should have been unrecognized until it was proved by the detailed mapping of the Geological Survey. The occurrence of certain species of graptolites affords a palæontological basis for placing on this horizon a considerable mass of slaty and gritty strata in Cardiganshire, and for identifying these and the typical Tarannon Shales with their probable equivalents in the Lake District and in Scotland. The following graptolitic zones in ascending order have been determined in the Tarannon rocks: (1) Rastrites maximus, (2) Monograptus exiguus, (3) Cyrtograptus Grayæ. Other common species are Monograptus

galaensis, M. priodon, M. riccartonensis, and Retiolites geinitzianus.

2. Wenlock Group.—This suite of strata includes the larger part of the known Upper Silurian fauna of Britain, as it has yielded more than 160 genera and 500 species. In the typical Silurian area of Murchison, it consists of two limestone bands (Woolhope and Wenlock),

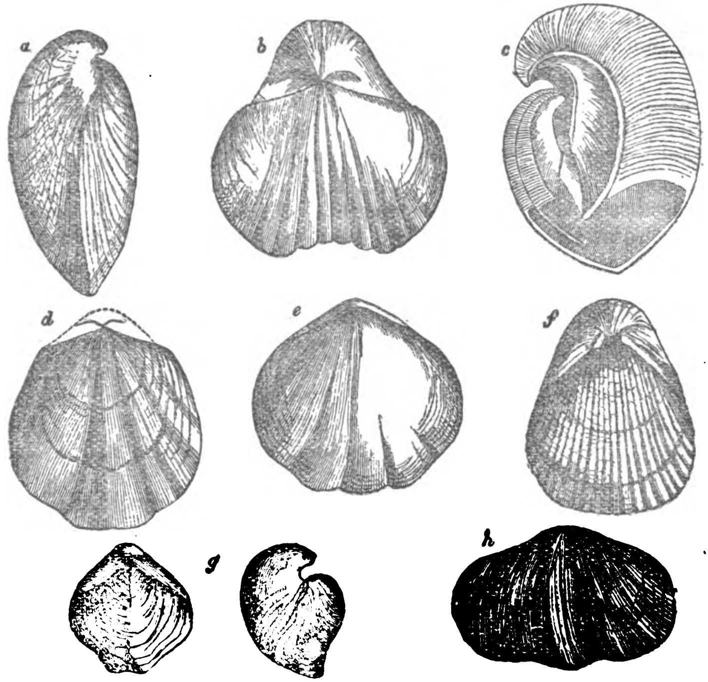

Fig. 344.—Group of Pentameri from Llandovery and Wenlock Rocks.
***a*, Pentamerus oblongus, Sby.; *b*, P. galeatus, Dalm.: *c*, P. Knightii, Sby.; *d*, P. oblongus, Sby.; *e*, P. rotundus, Sby. (?); *f*, P Knightii (small specimen); *g*, P. linguifer, Sby.; *h*, P. undatus, Sby.**

separated by a thick mass of shale (Wenlock Shale). The following sub-groups in ascending order are recognized:

(*a*) *Woolhope Limestone.*—In the original typical Upper Silurian tract of Shropshire and the adjacent counties, the Upper Llandovery rocks are overlain by a local group of gray shales containing nodular limestone, which here and there swells out into beds having an aggregate thickness of 30 or 40, but at Malvern as much as 150 feet. These

strata are well displayed in the picturesque valley of Woolhope in Herefordshire, which lies upon a worn quâ-quâ-versal dome of Upper Silurian strata, rising in the midst of the surrounding Old Red Sandstone. They are seen likewise to the northwest, at Presteign, Nash Scar, and Old Radnor in Radnorshire, and to the east and south, in the Malvern Hills (where they include a great thickness of shale below the limestone), and May Hill in Gloucestershire. Among the common fossils of these strata may be mentioned Illænus (Bumastus) barriensis, Homalonotus delphinocephalus, Phacops caudatus, Encrinurus punctatus, Acidaspis Brightii, Atrypa reticularis, Orthis calligramma, Strophomena imbrex, S. euglypha, Leptæna transversalis, Rhynchonella borealis, R. Wilsoni, Euomphalus sculptus, Orthoceras annulatum.

It is a feature of the older Palæozoic limestones to occur in a very lenticular form, swelling in some places to a great thickness and rapidly dying out, to reappear again perhaps some miles away with increased proportions. This local character is well exhibited by the Woolhope limestone. Where it disappears, the shales underneath and intercalated with it join on continuously to the overlying Wenlock shale, and no line for the Woolhope sub-group can then be satisfactorily drawn. The same discontinuity is strikingly traceable in the Wenlock limestone to be immediately referred to.

(*b*) *Wenlock Shale.*—This sub-group consists of gray and black shales, traceable from the banks of the Severn near Coalbrook Dale across Radnorshire to near Carmarthen—a distance of about 90 miles. The same strata reappear in the protrusions of Upper Silurian rocks which rise out of the Old Red Sandstone plains of Gloucestershire, Herefordshire, and Monmouthshire. In the Malvern Hills, they are estimated by Prof. Phillips to reach a thickness of 640 feet, but toward the north they thicken out to more than 2000 feet. On the whole, the fossils are identical with those of the overlying limestone. The corals, however, so abundant in that rock, are here comparatively rare. The brachiopods (Lingula, Leptæna, Orthis, Strophomena, Atrypa, Rhynchonella, Spirifer) are generally of small size—Orthis biloba, O. hybrida, and the large flat O. rustica being characteristic.[85]

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[85] As an example of the small size but extraordinary abundance of brachiopods in this formation reference may be made to the fact that a cartload of the shale from Buildwas was found by careful washing to contain no fewer than 4300 specimens of one species (*Orthis biloba*), besides a much greater bulk of

Of the higher mollusca, thin-shelled forms of Orthoceras are specially abundant. Among the trilobites, Encrinurus punctatus, E. variolaris, Calymene Blumenbachii, C. tuberculosa, Phacops caudatus, P. longicaudatus are common. Distinctive species of graptolites characterize the shales of this group. At the base lies the zone of Cyrtograptus Murchisoni, with Monograptus priodon, M. Halli, M. vomerinus, M. colonus and Retiolites geinitzianus. Higher up comes the zone of Cyrtograptus Linnarssoni and still higher that of Monograptus testis. The most abundant Wenlock species in Britain are M. vomerinus, M. riccartonensis, and M. priodon, which last does not appear to reach the Lower Ludlow rocks.[86]

(*c*) *Wenlock Limestone.*—This is a thick-bedded, sometimes flaggy, usually more or less concretionary limestone, gray or pale pink, often highly crystalline, occurring in some places as a single massive bed, in others as two or more bands separated by gray shales, the whole forming a thickness of rock ranging from 100 to 300 feet. As its name denotes, it is typically developed along Wenlock Edge in Shropshire, where it runs as a prominent ridge for fully 20 miles; also between Aymestry and Ludlow. It likewise appears at the detached areas of Upper Silurian strata above referred to, being specially well seen near Dudley (whence it is often spoken of as the Dudley limestone), Woolhope, Malvern, May Hill, and Usk in Monmouthshire.

A distinguishing characteristic of the Wenlock limestone is the abundance and variety of its corals, of which no fewer than 24 genera and upward of 80 species have been described. The rock seems, indeed, to have been formed in part by massive sheets and bunches of coral. Characteristic species are Halysites catenularia, Heliolites interstinctus, H. tubulatus, Alveolites Labechei, Favosites aspera, F. fibrosa, F. gotlandica, Cœnites juniperinus, Syringopora fascicularis, Omphyma subturbinatum. The crinoids are also specially abundant, and often beautifully preserved, Periechocrinus moniliformis being one of the most frequent; others are Crotalocrinus rugosus, Cyathocrinus goniodactylus, and Marsupiocrinus cælatus. Several cystideans occur, of which one

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other brachiopods, amounting together to 10,000 specimens at least; while from seven tons weight of the shale at least 25,000 specimens of *Orthis biloba* were obtained.—Davidson and Maw, Geol. Mag. 1881, p. 101.

[86] Lapworth, Ann. Mag. Nat. Hist. v. 1880, p. 369.

is Pseudocrinites quadrifasciatus. More than 30 species of annelids have been found. The crustaceans include numerous trilobites, one of the most abundant being the long-lived Calymene Blumenbachii, which ranges from the Llandeilo flags (possibly from a still lower horizon) up to near the top of the Upper Silurian formations. It occurs abundantly at Dudley, where it received the name of the "Dudley Locust." Other common forms are Encrinurus punctatus, E. vario-

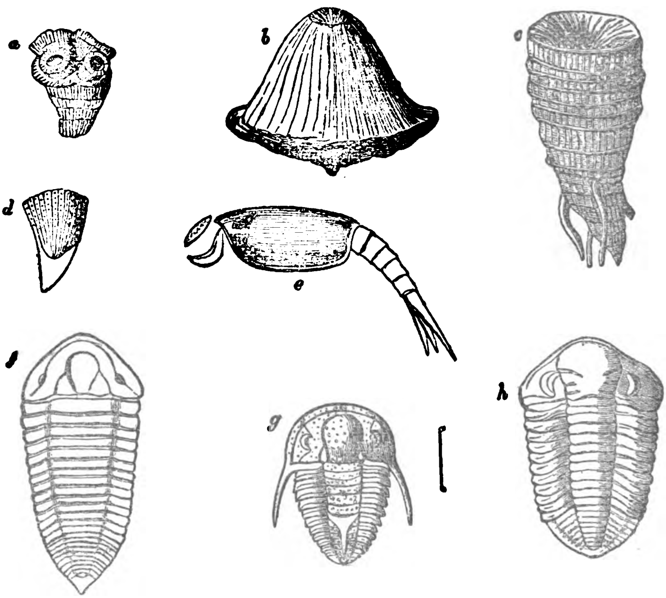

Fig. 845.—Upper Silurian Corals and Crustaceans.

a, Acervularia ananas, Linn.; *b*, Ptychophyllum patellatum, Schloth (½); *c*, Omphyma subturbinatum, Linn. (½); *d*, Petraia bina, Lons.; *e*, Ceratiocaris papilio, Salt. (½); *f*, Homalonotus delphinocephalus, Green (¼); *g*, Cyphaspis megalops, McCoy; *h*, Phacops Downingiæ, Murch.

laris, Phacops caudatus, P. Downingiæ, P. Stokesii, Illænus (Bumastus) barriensis, Homalonotus delphinocephalus, and Cheirurus bimucronatus. One of the most remarkable features in the crustacean fauna is the first appearance of the merostomata, which are represented by Eurypterus punctatus, Hemiaspis horridus, and Pterygotus problematicus. The brachiopods continue to be abundant, about 20 genera and 100 species having up to this time been enumerated. Among typical species may be noted Atrypa reticularis,

Whitfieldia (Meristella) tumida, Spirifer elevatus, S. plicatellus, Rhynchonella borealis (very common), R. cuneata, R. Wilsoni, Orthis elegantula, O. hybrida, Strophomena rhomboidalis, and Pentamerus galeatus. The lamellibranchs are abundant and are represented by species of Avicula, Pterinea, Cardiola, and Cucullella, with Grammysia cingulata, Orthonota amygdalina, and some species of Modiolopsis and Ctenodonta. The gasteropods are marked by species of Euomphalus, Murchisonia, Holopella, Acroculia, Cyclonema. The cephalopods are confined to five genera, Lituites, Actinoceras, Cyrtoceras, Orthoceras, and Phragmoceras; of these the orthoceratites are by far the most abundant both in species and individuals, Orthoceras annulatum being the most common form. The pteropods appear in the beautiful and abundant Conularia Sowerbyi, and the heteropods in the common and characteristic Bellerophon wenlockensis.

3. Ludlow Group.—This group consists essentially of shales, with occasionally a calcareous band in the middle. It graduates downward into the Wenlock group, so that when the Wenlock limestone disappears, the Wenlock and Ludlow shales form one continuous argillaceous formation, as they do where they stretch to the southwest through Brecon and Carmarthen. The Ludlow rocks, typically seen between Ludlow and Aymestry, appear likewise at the detached Silurian areas from Dudley to the mouth of the Severn. They were arranged by Murchison in three subgroups—Lower Ludlow Rock, Aymestry Limestone, and Upper Ludlow Rock.

(*a*) *Lower Ludlow Rock.*—This sub-group consists of soft dark gray to pale greenish-brown or olive sandy shales, often with calcareous concretions. Much of the rock, however, presents so little fissile structure as to get the name of mudstone, weathering out into concretions which fall to angular fragments as the rock crumbles down. It becomes more sandy and flaggy toward the top. From the softness of the shales, this zone of rock has been extensively denuded, and the Wenlock limestone rises up boldly from under it. It attains a thickness of 750 feet at Malvern.

An abundant suite of fossils is contained in these shales. Eight species of star-fishes have been found, belonging to the genera Protaster (like the brittle-stars of the British seas), Palæodiscus, and Palæocoma. The graptolites which played so conspicuous a part in the marine fauna of Cambrian and Silurian time now appear for the last time. They

are restricted entirely to the genus Monograptus, of which M. Nilssoni, M. colonus, M. leintwardinensis, M. Salweyi, M. bohemicus, M. scanicus, M. priodon (var. ludensis), and M. Roemeri are especially characteristic. The distinctive graptolitic zone of this part of the Silurian series has been named that of Monograptus Nilssoni, and is the last of the long series.

A few corals occur in the Lower Ludlow rock, all of species that had already appeared in the Wenlock limestone, but the conditions of deposit were evidently unfavorable for their growth. The trilobites are less numerous than in older groups; they include the venerable Calymene Blumenbachii; also Phacops caudatus, P. constrictus, P. Downingiæ, Acidaspis coronatus, Cheirurus bimucronatus, Encrinurus punctatis, Lichas anglicus, Homalonotus delphinocephalus, H. Knightii, and Cyphaspis megalops. But other forms of crustacean life occur in some number. As the trilobites began to wane, numerous phyllopods appeared, the genus Ceratiocaris being represented by nine or more species. Still more remarkable, however, was the increasing importance of the merostomatous crustaceans (Œurypterus, Hemiaspis, Pterygotus). Though brachiopods are not scarce, hardly any seem to be peculiar to the Lower Ludlow rock, nearly all of the known species occurring in the Wenlock group. Rhynchonella Wilsoni, Spirifer exporrectus, S. crispus, S. bijugosus, Strophomena euglypha, S. rhomboidulis, Atrypa reticularis, Discina Morrisii, Lingula lata, and L. Lewisii are not infrequent. Among the more frequently recurring species of lamellibranchs the following may be named—Cardiola interrupta, C. striata, Ctenodonta sulcata, Grammysia cingulata, Modiolopsis gradata, M. Nilssoni, Orthonota amygdalina, O. rigida, O. semisulcata, and a number of species of Pterinea. Among the gasteropods not uncommon species are Cyclonema corallii, Euomphalus alatus, Holopella gregaria, Loxonema sinuosa, and Murchisonia Lloydii. The old heteropod genus Bellerophon is still represented (B. expansus). The cephalopods abound, the genus Orthoceras being the prevalent type (O. angulatum, O. annulatum, O. bullatum, O. ludense, O. subundulatum, O. tracheale), but with species of Exosiphonites, Lituites, and Phragmoceras. The numbers of straight and curved cephalopods form one of the distinguishing features of the zone. At one locality, near Leintwardine in Shropshire, which has been prolific in Lower Ludlow fossils, particularly in star-fishes and eurypterid crustaceans, a fragment of the fish Scaphaspis (Pteras-

pis) ludensis was discovered in 1859. This is the earliest trace of vertebrate life yet detected in Britain. It is interesting to note that this fish does not stand low in the scale of organization, but has affinities with our modern sturgeon.

(*b*) *Aymestry Limestone*—a dark gray, somewhat earthy, concretionary limestone in beds from 1 to 5 feet thick. Where at its thickest (from 30 to 40 feet) it forms a conspicuous feature, rising above the soft and denuded Lower Ludlow shales. Owing to the easily removable nature of some fullers'-earth on which it lies, it has here and there been dislocated by large landslips. It is still more inconstant than the Wenlock limestone. Though well developed at Aymestry in Herefordshire, it soon dies away into bands of calcareous nodules, which finally disappear, and the lower and upper divisions of the Ludlow group then come together. The organic remains at present known are for the most part identical with Wenlock forms. It is evident that the organisms which flourished so abundantly in the clear water wherein the Wenlock limestone was accumulated, continued to live outside the area of deposit of the Lower Ludlow rock, and reappeared in that area with the return of the conditions for their existence during the deposition of the Aymestry limestone. The most characteristic fossil of the latter rock is the Pentamerus Knightii; other common forms are Rhynchonella Wilsoni, Lingula Lewisii, Strophomena euglypha, Atrypa reticularis, Bellerophon dilatatus, Pterinea Sowerbyi, with many of the same shells, corals, and trilobites found in the Wenlock limestone. Indeed, as Murchison has pointed out, except in the less number of species and the occurrence of some of the shells more characteristic of the Upper Ludlow zone, there is not much palæontological distinction between the two limestones.[87]

(*c*) *Upper Ludlow Rock.*—In the original Silurian district described by Murchison, the Aymestry limestone is covered by a calcareous shelly band full of Rhynchonella navicula, sometimes 30 or 40 feet thick. This layer is succeeded by gray sandy shale or mudstone, often weathering into concretions, as in the Lower Ludlow zone, and assuming externally the same rusty-brown or grayish olive-green hue. Its harder beds are quarried for building stone; but the general character of the deposit, like that of the argillaceous portions of the Upper Silurian formations as a whole, in the typical district of Siluria, is soft, incoherent, and crumbling, easily de-

[87] "Siluria," p. 130.

composing once more into clay or mud, and presenting, in this respect, a contrast to the hard, fissile, and often slaty shales of the Lower Silurian series. Many of the sandstone-beds are crowded with ripple-marks, rill-marks, and annelid-trails, indicative of the shallow littoral waters in which they were deposited. One of the uppermost sandstones is termed the "Fucoid Bed," from the number of its cylindrical seaweed-like stems. It likewise contains numerous inverted pyramidal bodies, which are believed to be casts of the cavities made in the muddy sand by the rotary movement imparted by tides or currents to crinoids or seaweeds rooted and half buried in it.[88] At the top of the Upper Ludlow rock, near the town of Ludlow, a brown layer occurs, from a quarter of an inch to three or four inches in thickness, full of fragments of fish, Pterygotus, and shells. This layer, termed the "Ludlow Bone-bed," is the oldest from which any considerable number of vertebrate remains has been obtained. In spite of its insignificant thickness, it has been detected at numerous localities from Ludlow as far as Pyrton Passage, at the mouth of the Severn—a distance of 45 miles from north to south, and from Kington to Ledbury and Malvern—a distance of nearly 30 miles from west to east; so that it probably covers an area (now largely buried under Old Red Sandstone) not less than 1000 square miles in extent. Yet it appears never to exceed, and usually to fall short of, a thickness of 1 foot. Fish remains, however, are not confined to this horizon, but have been detected in strata above the original bone-bed at Ludlow.

A considerable suite of organic remains has been obtained from the Upper Ludlow rock, which, on the whole, are the same as those in the zones underneath. Some minute globular bodies, doubtfully referred to the sporangia, of a lycopod (pachytheca[89]), occur with some other plant remains (Pachysporangium, Actinophyllum, Chondrites—a beautiful seaweed). Corals, as might be supposed from the muddy character of the deposit, seldom occur, though Murchison mentions that the incrusting form Favosites fibrosus may not infrequently be found enveloping shells; Cyclonema corallii and Murchisonia coralli being, as their names imply, its favorite habitats. All the corals of the Ludlow group are also Wenlock species. Some annelids (Serpulites longis-

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[88] Op. cit. p. 133.

[89] See Q. J. Geol. Soc. xxxviii. 1882, p. 107. Mr. Carruthers suggests that they are possibly the remains of an animal rather than a plant.

simus, Cornulites serpularius, and Trachyderma coriaceum) are not uncommon. The crustacea are represented in the Upper Ludlow rock by ostracods (Beyrichia Kloedeni, Leperditia marginata, Entomis tuberosa), phyllopods (Ceratiocaris, Dictyocaris), and more especially by eurypterids (Eurypterus, Hemiaspis, Pterygotus, Slimonia, Stylonurus, Himantopterus). The trilobites have still further waned in the Upper Ludlow rock, though Homalonotus Knightii, Encrinurus punctatus, Phacops Downingiæ, and a few others still occur, and even the persistent Calymene Blumenbachii may occasionally be found. Of the brachiopods, the most abundant forms in this group are Lingula minima, L. lata, Discina rugata, Rhynchonella Wilsoni, Strophomena filosa, and Chonetes striatella. The most characteristic lamellibranchs are Orthonota amygdalina, Goniophora cymbæformis, Pterinea lineata, P. retroflexa; some of the commonest gasteropods are Murchisonia corallii, Platyschisma helicites, and Holopella obsoleta. The orthoceratites are specifically identical with those of the Lower Ludlow rock, and are sometimes of large size, Orthoceras bullatum being specially abundant. The fish-remains consist of bones, teeth, shagreen-like scales, plates, and fin-spines. They include some plagiostomous (placoid) forms (Thelodus), shagreen-scales (Sphagodus), and some ostracosteans, Cephalaspis (C. ornatus, C. Murchisoni), Auchenaspis (A. Salteri), Pteraspis (P. Banksii), Scaphaspis (S. ludensis), and Eukeraspis (Plectrodus) (E. mirabilis). Some of the spines described under the name of Onchus are probably crustacean.

(*d*) *Tilestones, Downton Castle Stone and Ledbury Shales.*—Above the Upper Ludlow shales and mudstones lies a group of fine yellow, red, and gray micaceous sandstones from 80 to 100 feet thick which have long been quarried at Downton Castle, Herefordshire. At Ledbury these sandstones are surmounted by a group of red, purple, and gray marls, shales, and thin sandstones, having a united thickness of nearly 300 feet. Originally the whole of these flaggy upper parts of the Ludlow group were called "Tilestones" by Murchison, and, being often red in color, were included by him as the base of the Old Red Sandstone, into which they gradually and conformably ascend. They point to a gradual change of physical conditions, which took place at the close of the Silurian period in the West of England and brought in the peculiar deposits of the Old Red Sandstone. There is every reason to believe that for a long time the marine sedimentation of Upper Silurian type continued to

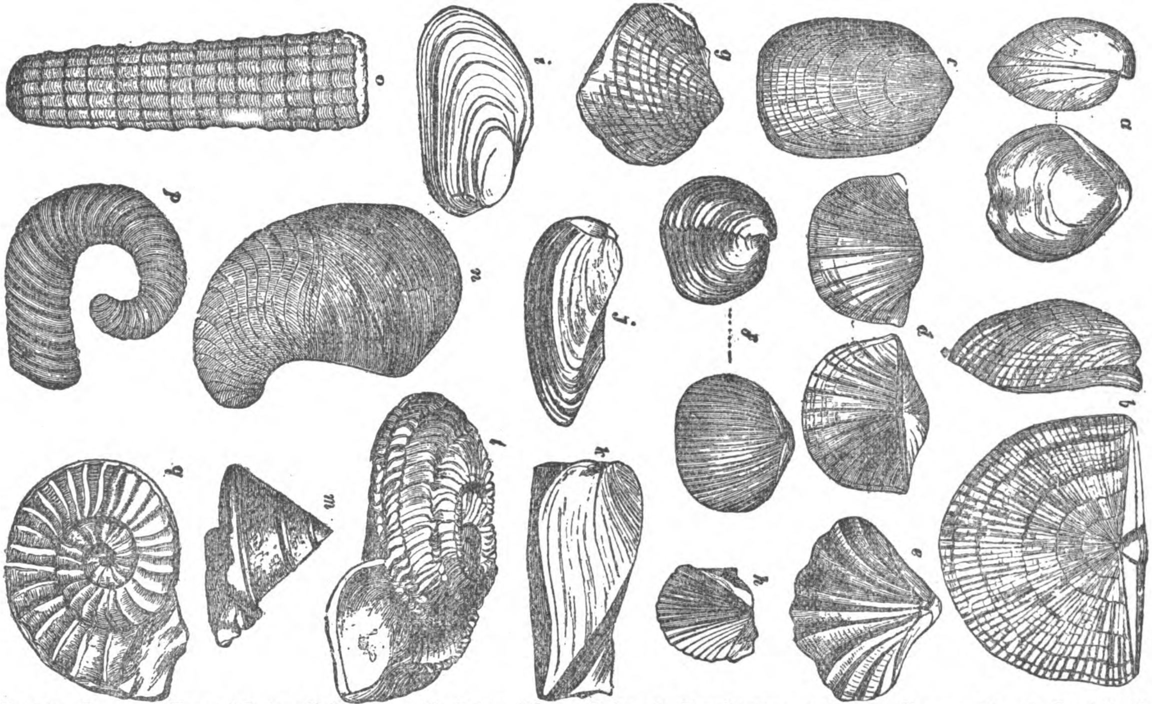

Fig. 346.—Group of Upper Silurian Mollusca. *a*, Meristina didyma, Dalm.; *b*, Strophomena antiquata, Sby.; *c*, Lingula Lewisii, Sby.; *d*, Leptæna transversalis, Dalm.; *e*, Rhynchonella borealis, Schloth.; *f*, Rhynchonella Wilsoni, Sby.; *g*, Cardiola interrupted, Brod.; *h*, Ambonychia acuticostata, McCoy; *i*. Modiolopsis Nilssoni, His.; *j*. Orthonota amygdalina, Sby.; *k*. Goniophora cymbæformis, Sby.; *l*, Euomphalus rugosus, Sby.; *m*, Trochus cælatus, McCoy ($\frac{3}{1}$); *n*, Phragmoceras ventricosum, Sby. ($\frac{1}{4}$); *o*, Orthoceras annulatum, Sby. ($\frac{1}{2}$); *p*, Lituites giganteus, Sby. ($\frac{1}{4}$); *q*, Lituites articulatus, Sby.

prevail in some areas, while the probably lacustrine type of the Old Red Sandstone had already been established in others, and that by the breaking down or submergence of the barriers between these different areas, marine and lacustrine conditions alternated in the same region. The Tilestones are the records of this curious transitional time.[90]

Vegetable remains, some of which seem to be fucoids, but most of which are probably terrestrial and lycopodiaceous, abound in the Downton sandstone and passage-beds into the Old Red Sandstone. The eurypterid genera still continue to occur, together with phyllopods (Ceratiocaris) and vast numbers of the ostracod Beyrichia (B. Kloedeni). Prevalent shells are Lingula cornea and Platyschisma helicites. The Ludlow fishes are also met with.

In the typical Silurian region of Shropshire and the adjacent counties, nothing can be more decided than the lithological evidence for the gradual disappearance of the Silurian sea, with its crowds of graptolites, trilobites, and brachiopods, and for the gradual introduction of those geographical conditions which brought about the deposit of the Old Red Sandstone. The fine gray and olive-colored muds, with their occasional zones of limestone, are succeeded by bright red clays, sandstones, cornstones, and conglomerates. The evidence from fossils is equally explicit. Up to the top of the Ludlow rocks, the abundant Silurian fauna continues in hardly diminished numbers. But as soon as the red strata begin the organic remains rapidly die out, until at last only the fish and the large eurypterid crustaceans continue to occur.

Turning now from the interesting and extremely important, though limited, area in which the original type of the Upper Silurian rocks is developed, we observe that, whether traced northward or southwestward, the soft mudstones and thick limestones give way to hard slates, grits, and flagstones, among which it is scarcely possible sometimes to discriminate what represents the Wenlock from what may be the equivalent of the Ludlow group. It is in Denbighshire and the adjacent counties that this change becomes most marked. The Tarannon shale above described passes into that region of North Wales, where

[90] On these passage-beds see Symonds, "Records of the Rocks," 1872, pp. 183–215; Q. J. Geol. Soc. xvi. 1860, p. 193; Roberts and Randall, op. cit. xix. 1863, p. 229; also the remarks made on the corresponding strata in Scotland, postea, p. 1271.

it forms the base of the Upper Silurian formations. It is covered by a series of grits, flags, sandstones, mudstones, and shales, which in some places are at least 3000 feet thick. These are overlain by and pass laterally into hard shales, and are believed to represent the true Wenlock group, perhaps even some portion of the Ludlow rocks. The zone of Cyrtograptus Murchisoni which marks the lower part of the Wenlock group is found in Denbighshire, and gives a recognizable horizon. It is evident, however, that in spite of the wide extent over which these Upper Silurian rocks of North Wales are spread, and the great thickness which they attain, they do not present an adequate stratigraphical equivalent for the complete succession in the

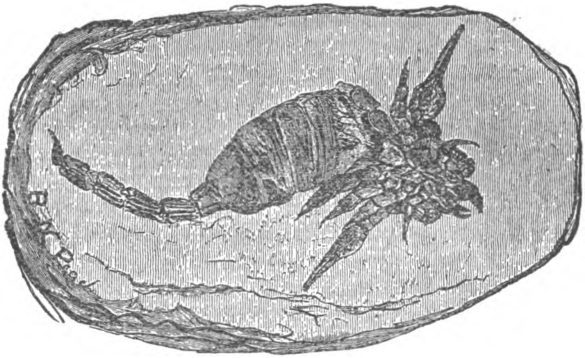

Fig. 347.—Fossil scorpion (*Palæophoneus*), Upper Silurian, Lesmahagow, Lanarkshire (about twice nat. size). Drawn by Mr. B. N. Peach.

original Silurian district. Instead of passing up conformably into the base of the Old Red Sandstone, as at Ludlow, they are covered by that formation unconformably. In fact they have been upturned, crumpled, faulted, and cleaved before the deposition of those portions of the Old Red Sandstone (Upper) which lie upon them. These great physical changes took place in Denbighshire when, so far as the evidence goes, there was entire quiescence in the Shropshire district; yet the distance between the two areas was not more than about 60 miles. These subterranean movements were doubtless connected with those more widely extended upheavals that converted the floor of the Silurian sea into a series of isolated basins, in which the Old Red Sandstone was laid down.

In Westmoreland and Cumberland a vast mass

of hard slates, grits and flags was identified by Sedgwick as of Upper Silurian age. These form the varied ranges of hills in the southern part of the Lake District, from near Shap to Duddon mouth. The following are the local subdivisions, with the conjectural equivalents in Siluria:[91]

Kirkby Moor Flags Hay Fell Flags (2000 feet)	Thick beds of hard sandstone, massive and concretionary or flaggy and micaceous (Phacops Downingiæ, P. caudatus, Ceratiocaris inornatus, Lingula cornea, Orthis lunata, Orthonota amygdali a, Holopella gregaria, H. conica).	=Upper Ludlow Group
Bannisdale Flags (5200 feet)	Calcareous beds (Rhynchonella navicula abundant) probably equivalent to the Aymestry Limestone. Sandstone and Shale, with star-fishes (Protaster). Dark blue flags and grits of great thickness. (Monograptus leintwardinensis ranges through the Bannisdale Flags and M. colonus and M. Salweyi also occur.)	=Middle Ludlow Group
Coniston Grits (upward of 4000 feet)	Flags and graywacke generally unfossiliferous, but containing Monograptus colonus, M. Bohemicus M. Roemeri, Cardiola interrupta, Orthoceras, angulatum, O. primævum, Ceratiocaris Murchi oni.	
Coniston Flags (2800 feet)	Dark gray course flags divided by Sedgwick into stages which are characterized by Mr. Marr as follows: Upper Coldwell Beds (lower part of zone of Monograptus bohemicus) with M. Colonus, M. Roemeri, Spirorbis Lewisii, Ceratiocaris Murchisoni, Encrinurus punctatus, Phacops Stokesii, Cardiola interrupta, Pterinea subfalcata, Orthocerus primævum, O. dimidiatum, O. subundulatum, O. indense. Middle Coldwell Beds (zone of Phacops obtusicaudatus) with Cardiola interrupta Orthoceras subannulare, O. angulatum, O. lineatum, O. inbricatum. Lower Coldwell Beds (zone of Monograptus Nilssoni).	=Lower Ludlow Group
	Brathy Flags (zone of Cyrtograptus Murchisoni), fossils chiefly graptolites including Monograptus priodon, M. vomerinus M. caltellus, Retiolites geinitzianus, Aptychopsis. Cardiola interrupta, Orthoceras primævum. Thickness more than 1000 feet.	Wenlock Group
Stockdale Shales (200-450 feet)	Browgill Beds: Upper pale green and purple shales with badly preserved fossils, 67 feet. Lower pale shales (65 feet) with zones of Monograptus crispus and M. turriculatus.	=Llandovery Group
	Skelgill Beds or Graptolitic Mudstones: Upper blue mudstones with two bands of black and blue graptolitic shale, the upper of which contains Monograptus spinigerus, the lower M. Clingani. Middle blue mudstones with three bands of dark graptolitic shale, the highest being the zone of Monograptus convolutus, (with M. gregarius, M. Clingani, Rastrites peregrinis and many other grsptolites), the middle being the zone of Monograptus argenteus (with M. gregarius, M. leptotheca, and ten other species; Rastrites peregrinus, and three other species; Diplograptus tamariscus, D. Hughesii, Climacograptus normalis, and other fossils); and the lower band being the zone of Monograptus fimbriatus, M. gregarius, M. Tenuis, and other species; Rastrites peregrinus, Diplograptus tamariscus, petalograptus ovatus, Climacograptus normalis. Lower calcareous shales=zone of Dimorphograptus confertus, with Monograptus revolutus, M. tenuis, Diplograptus vesiculosus, etc., resting on a thin limestone with Atrypa flexuosa.	

In some places beneath these shales a conglomeratic band occurs that forms their base and lies unconformably on Lower Silurian strata.

[91] For papers on the Upper Silurian rocks of the Lake District see Harkness and Nicholson, Quart. Journ. Geol. Soc. xxiv. 1868, p. 296; xxxiii. 1877, p. 461. H. A. Nicholson, op. cit. p. 521; xxviii. 1872, p. 217, "An Essay on the Geology of Cumberland and Westmoreland," 1868. Nicholson and Lapworth, Brit. Assoc. 1875, sects. p. 78. Geol. Survey Memoirs, Explanations of Sheet 98, S.E. and N.E. 1872 (Aveline and Hughes). Marr, Quart. Journ. Geol. Soc. xxxiv. 1878, p. 871; Geol. Mag. 1892, p. 534; Marr and Nicholson, Quart. Journ. Geol. Soc. xliv. 1888, p. 654.

In the northern part of the Lake District a great anticlinal fold takes place. The Skiddaw slates arch over and are succeeded by the base of the volcanic series above described. But before more than a small portion of that series has appeared, the whole Silurian area is overlapped unconformably by the Carboniferous Limestone. It is necessary to cross the broad plains of Cumberland and the south of Dumfriesshire before Silurian rocks are again met with. In this intervening tract, a synclinal fold must lie, for in the south of Scotland a broad tract of Upper Silurian strata is now known to form the greater part of the pastoral uplands which stretch from the Irish Sea to the North Sea. Its northern limit, where it rests conformably upon and passes down into the Caradoc group, extends from a little south of Port Patrick northeastward to near Dunbar. The strata throughout this region have been thrown into innumerable folds which are often reversed. The result of this disturbance has been to compress the rocks into highly inclined positions, and to keep the same group at the surface over a great breadth of ground, so that in spite of their steep angles of dip the strata are made to occupy as much space on the map as if they were almost flat. Here and there, where the anticlines are more pronounced and denudation has proceeded far enough, long boat-shaped inliers of Lower Silurian rocks have been laid bare underneath the upper series of formations. In this way the Llandeilo volcanic group can be traced by occasional exposures for some 90 miles to the northeastward from the Ayrshire coast where it is most largely developed. By far the larger part of the Uplands is formed of rocks which, from the researches of Prof. Lapworth among their graptolitic contents, are now known to be the general equivalents of the Llandovery group. Wenlock and Ludlow rocks occur on both sides of the Uplands. Toward the northeast the general lithological characters of the Upper Silurian are comparatively uniform—thick masses of graywacke and shale, with pebbly layers and well-marked bands of graptolitic black shale. This uniformity is accompanied by a corresponding monotony in the organic remains, which consist almost wholly of graptolites, confined for the most part to the zones of black shale, in which they are thickly crowded. But toward the southwest in Carrick (Ayrshire) there is a much greater diversity of sedimentation, thick masses of conglomerate, limestone and calcareous shale being conspicuous. In that district accordingly there is so marked a contrast in the abundance and variety of the

organic remains, that the strata may be compared with the more fossiliferous deposits of the original and typical Silurian region. The following table (page 1273) shows the succession of strata which follow continuously those given in the table on page 1252.[92]

Silurian rocks cover large continuous tracts in the northeast and southeast of Ireland, while at many places in the interior of the island, even to the western coast, they rise up in isolated areas from under younger formations. It is evident that, except where Cambrian and pre-Cambrian rocks appear, they spread across the whole country, though now so largely concealed by the Carboniferous formations. The Scottish type of sediments and of fossils is prolonged into Down and the other counties in the northeast and east. As already stated, the Glenkiln shales with their characteristic graptolites, traced to the southwestern coast-line of Scotland, reappear in full force on the Irish shore, and strike inland along the same persistent southeasterly line. They are found as far south as the southern coast of County Waterford and as far west as the flanks of the Slieve Bernagh Mountains in County Clare. In like manner the Hartfell or Caradoc-Bala shales with their distinctive graptolites are found in County Down, and probably occur in many other districts, while the Llandovery group of Birkhill has been recognized not only in Down, but in Tyrone, Fermanagh, and other counties. Abundant evidence of contemporaneous volcanic action has been obtained from the Silurian rocks of the east of Ireland.[93] Upper Silurian rocks representing the Llandovery and Wenlock formations attain an enormous development in the west of Ireland. In the picturesque tract between Lough Mask and Killary Harbor, where they reach a thickness of more than 7000 feet, they consist of massive conglomerates, sandstones, and shales, with Llandovery and Wenlock fossils and intercalated felsites, diabases and tuffs. Again, in the Dingle promontory of County Kerry, Upper Silurian strata full of Wenlock fossils contain the most impressive proofs of contemporaneous volcanic action; agglomerates, tuffs, and volcanic blocks

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[92] See Lapworth, Quart. Journ. Geol. Soc. xxxiv. 1878, xxxviii. 1882; Geol. Mag. 1889, pp. 20, 59; Ann. Mag. Nat. Hist. 1879, 1880.

[93] Quart. Journ. Geol. Soc. xlvii. 1891, Presidential Address, p. 150, and authorities there cited.

	Pentlands and northern part of region.	Central part of region.	Ayrshire and southern part of region.
Ludlow Group.	Yellow and brown mudstones, shales and sandstones passing up into base of Lower Old Red Sandstones, with many Ludlow fossils (*Leptæna transversalis, Orthonota amygdalina, Platyschisma helicites, Orthoceras Maclareni, Beyrichia Kloedeni, Ceratiocaris, Dictyocaris, Eurypterus, Pterygotus, Slimonia, Stylonurus*, &c.)		Flaggy shales, grey grits, and conglomerates (Straiton), with *Beyrichia Kloedeni, Pterygotus, Ceratiocaris*, &c.
Wenlock Group.	Blue, grey, and brown shales, greywackes and flaggy grits with some Wenlock fossils (*Monograptus vomerinus, M. colonus, M. priodon, Retiolites geinitzianus*).		Blue, grey, and yellow flagstones and shales, with *Monograptus vomerinus, Cardiola*, &c. Purple sandstones and calcareous bands (Penkill, Dailly), with *Cyrtograptus Grayæ, Retiolites geinitzianus*, and Wenlock fossils.
Llandovery Group.	Thick group of grits and greywackes, with grey shales and flagstones (Queensberry grits, Gala group) the upper portion containing *Retiolites geinitzianus, Monograptus priodon*, the lower portion yielding *M. exiguus, M. crispus, Protovirgularia, Crossopodia*, &c.	Thick group of greywackes, grits, and grey shales (Hawick group of Roxburghshire, &c., Ardwell group of Dumfriesshire and Galloway), with *Protovirgularia, Crossopodia*, and *Monograptidæ*.	Purple shales and mudstones, grey and green flagstones, and grits with *Monograptus exiguus, M. galaensis, Protovirgularia, Crossopodia, Cruziana*, &c. (=Stockdale shales of Lake District). Limestone (Camregan) with *Pentamerus oblongus*.
Llandovery Group	Greywackes, flagstones, and shales, with occasional bands of conglomerate, some of which contain fragments of rocks like those of the Highlands. Thin leaves of black shale in this group (Queensberry in part, Dalveen and Haggis-rock groups of Geological Survey) contain Birkhill graptolites.	Greywackes and shales including the black graptolitic Birkhill shales which form two bands separated by alternations of grey and green shales, and are sub-divided as follows :—	
		Upper Birkhill. 3. Zone of *Rastrites maximus, Monograptus turriculatus*, &c. 2. Zone of *Monograptus spinigerus, M. distans*, &c. 1. Zone of *Monograptus Clingani*, with *M. crenularis, M. Sedgwicki, Petalograptus cometa*.	Greywackes, shales, and quartz-conglomerates, with *Monograptus turriculatus* and other Upper Birkhill graptolites. Limestone (Woodland Point), with *Pentamerus lens*, &c.
		Lower Birkhill. 3. Zone of *Monograptus gregarius*, with *M. fimbriatus, M. convolutus, Diplograptus folium, Rastrites peregrinus*, &c. 2. Zone of *Diplograptus vesiculosus*, with *Monograptus cyphus, M. tenuis*. 1. Zone of *Diplograptus acuminatus* with *Dimorphograptus elongatus? Monograptus attenuatus, M. tenuis*.	Sandstones, shales, and conglomerates, with the graptolites of the Lower Birkhill zones. Sandstones, grits, shales, and conglomerates, with *Meristella angustifrons, Diplograptus acuminatus* and other Lower Birkhill graptolites. The conglomerates contain the earliest traces of fragments of rocks like those of the Highlands in this region.

being intermingled with the fossiliferous strata, which are further separated by thick sheets of nodular felsitic lavas.[94]

Basin of the Baltic, Russia and Scandinavia.[95]—The broad hollow which, running from the mouth of the English Channel across the plains of northern Germany into the heart of Russia, divides the high grounds of the north and northwest of Europe from those of the centre and south, separates the European Silurian region into two distinct areas. In the northern of these we find the Lower and Upper Silurian formations attaining an enormous development in Britain, but rapidly diminishing in thickness toward the northeast, until, in the south of Scandinavia and the Gulf of Finland, they reach only about $\frac{1}{25}$th of that depth. Along the Baltic shores, too, they have on the whole escaped so well from the dislocations, crumplings, and metamorphisms so conspicuous along the northwestern European border, that to this day they remain over wide spaces nearly as horizontal and soft as at first. In the southern European area, Silurian rocks appear only here and there from amid later formations, and almost everywhere present proofs of intense subterranean movement. Though sometimes attaining considerable thickness they are much less fossiliferous than those of the northern part of the region, except in the basin of Bohemia, where an exceedingly abundant series of Silurian organic remains has been preserved.

In Russia, Silurian rocks must occupy the whole vast breadth of territory between the Baltic and the flanks of the Ural Mountains, beyond which they spread eastward into Asia. Throughout most of this extensive area they lie in horizontal undisturbed beds, covered over and concealed from view by later formations. Along the southern margin of the Gulf of Finland, they appear at the surface as soft

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[94] Op. cit. p. 159, and authorities cited. Consult on Irish Silurian rocks the Explanations to the one-inch Sheets of the Geological Survey.

[95] Consult Angelin's "Palæontologica Suecica," 1854; Kjerulf, "Norges Geologi," 1879, or "Geologie des Südl. Norvegen" (Gurlt), 1880; Linnarsson, Svensk. Vet. Akad. viii. No. 2; Zeitsch. Deutsch. Geol. Gesell. xxv. 675; Geol. Mag. 1876, pp. 145, 240, 287, 379; Geol. Föreningens Stockholm Förhandl. 1872–74, 1877, 1879; S. Törnquist, Kong. Vet. Akad. Förhandl. 1874, No. 4; Geol. Förn. Stockholm Förhandl. 1879; Lundgren, Neues Jahrb. 1878, p. 699; Brögger, "Die Silurischen Etagen 2 und 3 im Kristiania Gebiet," 1882; F. Schmidt, Q. J. Geol. Soc. 1882, p. 514; J. E. Marr, Quart. Journ. Geol. 1882. p. 313; A. G. Nathorst, "Sveriges Geologi," part i. 1892, and papers cited below.

clays, sands, and unaltered strata, which, so far as their lithological characters go, might be supposed to be of late Tertiary date, so little have they been changed during the enormous lapse of ages since Lower Palæozoic time. The great plains bounded by the Ural chain on the east, by the uplands of Finland and Scandinavia on the north, and by the rising grounds of Germany on the southwest, have thus from a remote geological antiquity been exempted from the terrestrial corrugations that have affected so much of the rest of Europe. They have been alternately, but gently, depressed as a sea-floor, and elevated into steppes or plains. But along the flanks of the Ural Mountains, the older Palæozoic rocks have been upheaved and placed on end or at a high angle against the central portions of that chain; and, according to the observations of Murchison, Keyserling and De Verneuil, have been partially metamorphosed into chlorite-schists, mica-schists, quartzites and other crystalline rocks. To the northwest also, over a vast region in Scandinavia, they have been subjected to gigantic displacements and great regional metamorphism (p. 1030).

Taking first their unaltered condition, we find them well exposed along the southern shores of the Gulf of Finland, in the Baltic provinces of Russia, where, according to F. Schmidt, they form with the Cambrian groups below them one continuous and conformable series, and are capable of arrangement as in the subjoined table:[96]

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[96] Mem. Ac. Imp. St. Petersb. (7) xxx. 1881, No. 1; Q. J. Geol. S. xxxviii. 1882, p. 514.

Upper Silurian.

Stage K. Upper Oesel Zone (50 or 60 ft. = Ludlow Group)—gray limestones and marls, yellow limestones: Spirifer elevatus, Chonetes striatella, Beyrichia tuberculata, Pterinea retroflexa; an abundant eurypterid fauna and fish remains (Onchus, Pachylepis).

" I. Lower Oesel Zone (60 ft. = Wenlock)—chiefly dolomites with marls: Orthoceras annulatum, Euomphalus funatus, Spirifer crispus, Orthis elegantula, Leptæna transversalis.

" H. Pentamerus-esthonus Zone—in the east, dolomites; in the west, gray coral limestone, with Pentamerus esthonus (oblongus), Syringopora bifurcata, Favosites gotlandica, Halysites (5 sp.)

" G.
- 3. Raiküll Beds (100 ft.)—coral-reefs and flagstones: Leperditia Keyserlingii, Phacops elegans.
- 2. Borealis Bank (40 ft.)—consisting almost entirely of agglomerated shells of Pentamerus borealis.
- 1. Jörden Beds (20–30 ft.)—thin calcareous flagstones and marls: Leperditia Hisingeri, Orthis Davidsoni, Strophomena pecten, Rhynchonella affinis.

Lower Silurian.

" F. (1) Lyckholm and (2) Borkholm Zones (100 ft. = Middle Bala or Caradoc), contain the most abundant fauna of all the stages: Phacops (Chasmops) macroura, Cheirurus octolobatus, Encrinurus multisegmentatus, Bellerophon bilobatus, Strophomena expansa, Orthis vespertilio, O. Actoniæ, O. insularis.

" E. Wesenberg Zone (30 ft. = Bala or Caradoc)—hard yellowish limestone, with marly partings: Leptæna sericea, Strophomena deltoidea, Orthis testudinaria, Phacops Nieszkowskii, P. wesenbergensis, Encrinurus Seebachi, Cybele brevicauda.

" D. Jewe Zone (100 ft.), consisting of a lower or Jewe band and an upper or Kegel band: Cheirurus pseudohemicranium, Hemicosmites extraneus, Lichas deflexa, L. illænoides, Chasmops bucculenta, Strophomena Asmusii.

" C.
- 3. Itfer Beds (20–30 ft.)—hard limestone with siliceous concretions; fauna nearly same as in C. 2, but with some peculiar trilobites, and some forms belonging to Stage D.
- 2. Kuckers Shale (Brandschiefer) consisting of bituminous marls and limestones (30–50 ft.): Phacops exilis, P. (Chasmops) Odini, Cheirurus spinulosus, Pleurotomaria elliptica, Porambonites teretior, Orthis lynx, Echinosphærites aurantium.
- 1. Echinosphærite Limestone, etc. (20–50 ft. = uppermost Orthoceratite Limestone of Sweden)—Echinosphærites aurantium, and Orthoceras regulare are the most characteristic fossils, with numerous trilobites.

" B.
- 3. Orthoceratite (Vaginaten-) Limestone (3–20 ft. = Orthoceras limestone of Scandinavia)—hard gray limestone crowded with Orthoceras commune and O. vaginatum; also Phacops sclerops, Cheirurus ornatus, Asaphus heros, Ampyx nasutus, etc.
- 2. Glauconite Limestone (12–40 ft.)—Megalaspis planilimbata, Cheirurus clavifrons, Asaphus expansus, Porambonites reticulatus, Orthis parva.
- 1. Glauconite Sand (Greensand), lying directly on the Cambrian Dictyonema shale (1–10 ft. = Ceratopyge Stage of Scandinavia)—Obolus siluricus, Siphonotreta, Lingula; "conodonts" of Pander.

In Scandinavia the following general order of succession has been established:

Upper Silurian.
- Limestones and marls (50-60 ft. in Gothland) with Ludlow fossils.
- Limestones and shales (150 ft. in Gothland) with Wenlock fossils (Monograptus ludensis, M. colonus, Retiolites geinitzianus).
- Marls and shales (with Llandovery forms) apparently unconformable on all older rocks.

Lower Silurian.
- Brachiopod shales (Trinucleus, Staurocephalus).
- Trinucleus shales and limestones.
- Middle graptolite shales (Llandeilo species of Didymograptus, Diplograptus, Climacograptus and other genera) which pass laterally into limestone, and are in different districts represented by the Chasmops limestone.
- Lower graptolite shales (Arenig species of Phyllograptus, Dichograptus, Didymograptus, and other genera) passing into the Orthoceras limestone, which is recognizable over a large part of southern Scandinavia.
- Ceratopyge limestone (Dicellocephalus, Agnostus, Niobe, Amphion, Obolus) and other fossils like those found at the base of the Arenig and in the Tremadoc group.

In Scania, the Silurian series has been subdivided into graptolitic zones as in the subjoined table:[97]

Upper Silurian.
- A. Upper Group—Cardiola shales, with limestone and sandstone.
- B. Middle Group, with the following zones in descending order: *a*, Cyrtograptus Carruthersi; *b*, C. rigidus; *c*, C. Murchisoni; *d*, Monograptus riccartonensis; *e*, Cyrtog. Lapworthii; *f*, C. (?) spiralis; *g*, C. Grayæ.
- C. Lower Group, composed of the following zones in descending order: *a*, Monograptus cometa; *b*, Gray unfossiliferous shales; *c*, Cephalograptus cometa; *d*, Mon. leptotheca; *e*, M. gregarius; *f*, M. Cyphus.

Lower Silurian.
- D. Upper Group, composed of the following zones in descending order: *a*, Diplograptus, sp.; *b*, Phacops mucronata; *c*, Staurocephalus clavifrons; *d*, Unfossiliferous marly shales; *e*, Niobe lata; *f*, Unfossiliferous shales; *g*, Diplograptus quadrimucronatus; *h*, Trinucleus, sp.; *i*, Calymene dilatata; *k*, Unfossiliferous shales.
- E. Middle Group—Graptolite shales, with zones of *a*, Climacograptus ragosus; *b*, C. styloideus; *c*, Black unfossiliferous shales; *d*, Limestone band, with Ogygia, sp.; *e*, Dicranograptus Clingani; *f*, Climacograptus Vasæ; *g*, Unfossiliferous shales; *h*, Cœnograptus gracilis; *i*, Thin apatitic band; *k*, Diplograptus putillus; *l*, Glossograptus; *m*, Gymnograptus Linnarssoni; *n*, Glossograptus; *o*, Didymograptus geminus (Murchisoni).
- F. Lower Group, composed of the zones of *a*, Phyllograptus, sp.; *b*, Orthoceras limestone; *c*, Tetragraptus shales (lower graptolite shales); *d*, Ceratopyge limestone.

The island of Gothland has long been celebrated for its development of Upper Silurian rocks. According to Lindstrom,[98] the following subdivisions are there traceable:

[97] S. A. Tullberg, "Skänes Graptoliter," Sverig. Geol. Undersökn. ser. c. No. 50, 1882-83.

[98] Neues Jahrb. 1888, i. p. 147, and F. Schmidt, op. cit. 1890, ii. p. 249.

Ludlow.

H. Cephalopoda and Stromatopora-Limestone (20–30 feet) with Phragmoceras, Ascoceras, Glossoceras.

G. Megalomus-Limestone (8–12 feet), with Megalomus Gotlandicus, Trimerella.

F. Crinoidal and Coral conglomerate (20 feet), a limestone made up of stems of crinoids, corals and other fossils. Among the crinoids are species of Crotalocrinus, Enallocrinus, Barrandeocrinus, Cyathocrinus; there occur also Spirifer Schmidti, Pentamerus conchidium. This band lies somewhere about the horizon of the Aymestry Limestone.

E. Pterygotus-clay or marl (1–2 feet) with abundant fragments of Pterygotus osiliensis, also Phasganocaris, Strophomena, Eatonia, Conularia, etc.

Wenlock.

D. Limestone, oolite and marly bands (50 feet) with numerous lamellibranchs; species of Pterinea, Aviculopecten and Grammysia, also Orthis basalis, O. biforata and Atrypa Angelini, Lichas, Cyclonema delicatulum, etc.

C. Younger marly shales and sandstone (100 feet), with a large and varied assemblage of fossils like those of the Wenlock Shale (Phacops Downingiæ, P. vulgaris, Homalonotus Knighti, Strophomena euglypha, Orthis biloba, Strophomena Walmstedti, Rhynchonella Wilsoni, Orthoceras annulatum, O. gregarium, Monograptus ludensis, M. colonus, Retiolites geinitzianus, etc.

Llandovery.

B. Stricklandinia-marl (8 feet) with Heliolites, Plasmopora, Halysites, Bronteus platyactin, Calymene papillosa, C. frontosa, Orthis Davidsoni, O. Lovéni, and especially the abundant Stricklandinia lyrata.

A. Older red marly shales (thickness unknown and not seen in place) with some 40 species of fossils, among which are Favosites gotlandica, F. Forbesi, Halysites, Plasmopora, Arachnophyllum difluens, etc.

In the Christiania district, according to Kjerulf, the following subdivisions can be established:

Upper.

Stage 8.

- γ. Compact gray, often bituminous limestone, with abundant Orthoceras cochleatum and Chonetes striatella.
- β. Gray, somewhat bituminous limestone, with shales and clays.
- α. Fissile green or gray marly shales containing the last graptolites. This and the two overlying members have a united depth of 835 Norwegian feet at Ringerige.

Stages 6 & 7. Coral limestone and Pentamerus limestone.

Lower.

Stage 5. Calcareous sandstone, with Rhynchonella diodonta and shales, 150 to 370 feet.

" 4. Shales and marls, with nodules and short beds of cement-stone (Trinucleus, Chasmops), 700 feet.

" 3. Graptolite shales, Limestone in two or more bands (Orthoceras-, Asaphus-, Megalaspis-limestone), 250 feet in places, resting upon the alum-shales of the Primordial zone.[99]

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[99] Prof. Brögger has further subdivided Stage 3 as follows, in ascending order: 3*a*, (α) Shales and limestones with Symphysurus incipiens, (β) Ceratopyge shales, (γ) Ceratopyge limestone; 3*b*, Phyllograptus shales; 3*c*, (α) Megalaspis limestone, (β) Expansus-shales, (γ) Orthoceras limestone, the whole stage having a thickness of about 47 metres in the Christiania district.—"Die Sil. Etagen."

In Easter and Wester Gothland patches of Silurian strata are met with preserved in horizontal sheets under an overlying capping of diabase. But when the rocks are traced into the western parts of Norway and through the central regions where the boundaries of Norway and Sweden meet, they present a remarkably different development from that just described. According to the researches of Kjerulf, Dahll, Tornebohm, Brögger, and Reusch, vast masses of quartzite, mica-slate, gneiss, hornblende-schist, clay-slate, and other crystalline rocks can be seen reposing upon recognizable Silurian strata in numerous natural sections. Not improbably these Scandinavian metamorphic rocks, like those occupying a similar position in Scotland, will be found to include portions of different pre-Cambrian systems which, together with the Cambrian and Silurian strata, have been subjected to such great disturbance as to have had a new crystalline structure superinduced upon them. Enormous displacements and lateral thrusts have driven the crystalline rocks over the fossiliferous strata, as in Scotland, but the details of this structure, which has been recognized by Tornebohm, have still to be worked out. As regards the date of these great earth-movements and metamorphism, it is important to remember that, as already stated (p. 1190), Upper Silurian fossils have been found by Reusch at Bergen in the crystalline schists themselves, as well as in the limestones intercalated in and underlying them.[100]

Western Europe.—The researches principally of Gosselet and Malaise have demonstrated that a considerable part of the strata grouped by Dumont in his "Terrain Rhénan," and generally supposed to be of Devonian age, must be relegated to the Silurian series.[101] Though almost concealed by younger formations, the Silurian rocks that are laid bare at the bottom of the valleys of the Ardennes can be paralleled in a general way as under:

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[100] See Dahll, Förh. Vedensk-Selskab. Christiania, 1867. Kjerulf, "Geologie des Süd. u. Mit. Norwegen," 1880. Törnebohm, Bihang K. Svensk. vet. Akad. Handl. i. No. 12, 1873; Geol. För. Stockhom Förhand. vi. 1883, p. 274; xiii. 1891, p. 37; xiv. 1892, p. 27; Nature, xxxviii. 1888, p. 127. Brögger, "Die Silurischen Etagen 2 und 3 im Kristianiagebiet," 1882, p. 352. Pettersen, Tromsö Museums Aarsheft, vi. 1883, p. 87. F. Svenonius, Neues Jahrb. 1882 (i.) p. 181. Nathorst, "Sveriges Geologi," p. 141.

[101] Gosselet, "Esquisse Geologique du Nord de la France," p. 34. "L'Ardenne," Mem. Carte Geol. France, 1888, p. 137. Mourlon, "Geol. de la Belgique," p. 40; Malaise, Mem. Couronn. Acad. Roy. Belgique, 1873; Bull. Acad. Roy. Belg. xx. 1890, p. 440. C. Barrois, Ann. Soc. Geol. Nord, xx. 1892, p. 75; in this work references are given to the literature of French Silurian geology.

Upper Silurian.	Ludlow.	Equivalents of the Ludlow rocks seen in the valley of the Fuette between Fosse and Malonne, containing Monograptus colonus, M. Nilssoni, Retiolites geinitzianus, Orthoceras, Cardiola interrupta, etc.
	Wenlock.	Brown sandy shales of Naninne, with Cyrtograptus Murchisoni, Monograptus bohemicus, M. Nilssoni, M. priodon, M. vomerinus, Retiolites geinitzianus, Cardiola interrupta, Orthoceras, etc.
	Llandovery.	Quartzites and sandstones of Grand-Manil, with Monograptus bohemicus, M. galaensis?, M. priodon, M. proteus, M. subconicus.
		Shales overlying the eurites of Grand-Manil, and containing Climacograptus normalis, C. rectangularis, Dimorphograptus elongatus, D. Swanstoni, Diplograptus modestus, Monograptus gregarius, M. leptotheca, M. tenuis.
Lower Silurian.	Caradoc.	Schistes de Gembloux; pyritous black and greenish shales, which at Grand-Manil, in the valley of the Orneau, have yielded Calymene incerta, Trinucleus setiformis, Illænus Bowmanni, Bellerophon bilobatus, Strophomena rhomboidalis, Orthis testudinaria, O. vespertilio, O. calligramma, O. Actoniæ, Climacograptus caudatus, C. styloideus, C. tubuliferus.
		The horizon of the Llandeilo rocks is doubtfully represented at Sart-Bernard.
	Arenig.	Graptolitic shales, with Climacograptus antennarius, C. Scharenbergi, Dichograptus octobrachiatus, Didymograptus Murchisoni, D. nanus, Diplograptus foliaceus, D. tricornis, Phyllograptus angustifolius, P. typus, Tetragraptus bryonoïdes, etc.
		Upper Cambrian horizons are represented at Spa and elsewhere by Dictyonema sociale.

The Silurian rocks of Belgium comprise several contemporaneously erupted masses of porphyrite and of diabase, as well as beds of porphyroid, arkose, and eurite.

Silurian rocks have been detected in many parts of the old Palæozoic ridge of the northwest of France. According to De Tromelin and Lebesconte,[102] the order of succession in Ille-et-Vilaine is as under:

Upper Silurian.	Wenlock.	White limestone of Erbray (Calymene Blumenbachii, Harpes venulosus).
		Ampelitic (carbonaceous) limestone of Briasse (Monograptus priodon, M. Hisingeri, M. colonus, M. vomerinus, M. jaculum).
		Sandy and ferruginous odules of Martigné-Ferchaud, Thourie, etc. (Cardiola interrupta, Monograptus priodon).
	Llandovery.	Ampelitic (carbonaceous) shales of Poligné (Monograptus crassus, M. Halli, M. priodon, M. jaculum, M. convolutus, M. continens, Diplograptus palmeus, Cephalograptus folium, Retiolites geinitzianus).
		Phtanites of Anjou (Monograptus convolutus, M. crenularis, M. lobiferus, M. sublobiferus, M. Sedgwicki, M. cyphus, M. crispus, M. Clingani, Cephalograptus folium, Diplograptus Hughesi, Rastrites peregrinus, R. Linnæi).

[102] De Tromelin and Lebesconte, Bull. Soc. Geol. France, 1876, p. 585; Assoc. Franç. (1875); *Bull. Soc. Linn. Normandie* (1877), p. 5. See also Dalimier, "Stratigraphie des Terrains primaires dans la presqu'ile de Cotentin," Paris, 1861;

Lower Silurian.	Llandeilo and Bala.	Slates of Riadan (Trinucleus).
		Sandstones (May, Thourie, Bas-Pont, Saint-Germain de la Bouexière, etc.), containing Trinucleus Goldfussi, Calymene Bayani, Orthis redux, O. budleighensis, O. pulvinata, O. valpyana, O. Berthosi, Nucleospira Vicaryi, Lingula Morierei, Pseudarca typa, Diplograptus foliaceus, D. angostifolius.
		Slates of La Couyère (Orthis Berthosi).
		Nodular shales of Guichen, etc. (Calymene Tristani, Placoparia Tourneminei, Acidaspis Buchii).
		Slates of Angers (Ogygia Desmaresti, Didymograptus Murchisoni, D. euodus, D. nanus, D. furcillatus).
		Shales of Laillé and Sion (Placoparia Zippei, Hyolithes cinctus).
	Arenig.	Armorican sandstone (Grès Armoricain), containing Asaphus armoricanus, Lingula Lesueuri, L. Hawkeii, L. Salteri, Dinobolus Brimonti, Lyrodesma armoricana, annelids.
		Red shales and conglomerates without fossils.

In Normandy, where the first French graptolites were found, some of the species characteristic of the uppermost groups of Brittany have been obtained. Silurian fossils have also been detected southward in Maine and Anjou, and still more abundantly from the ridge of old rocks which forms the high grounds of Languedoc where the following section has been determined.[103]

Shales and ampelitic orthoceratite limestones (200 metres) with Cardiola interrupta, Monograptus priodon, M. bohemicus, M. colonus, M. Roemeri, M. Nilssoni. This zone evidently corresponds with that of the English Wenlock group.

Alternations of shales and white cystidean limestones.

Shales with Orthis Actoniæ.

Green shales with concretions (gâteaux) formed around large trilobites, Asaphus Fourneti, Illænus Lebescontei, Didymograptus euodus. These strata are probably of Llandeilo age.

Sandstone and grit like the Grès Armoricain, about 50 metres thick, containing Cruziana, Vexillum, Lingula Lesueuri, Dinobolus Brimonti.

Shales with calcareous nodules (150 metres) containing Bellerophon Oehlerti, Agnostus, Calymene, Illænus, Megalaspis, Didymograptus balticus, D. pennatulus, D. nitidus, D. bifidus, D. indentus, Tetragraptus serra, T. quadribrachiatus. These strata and the overlying sandstone represent the British Arenig rocks.

Bull. Soc. Geol. France, 1862, p. 907; De Lapparent, Bull. Soc. Geol. France, 1877, p. 569; Barrois, Ann. Soc. Geol. Nord, iv. vii. and the memoirs cited below.

[103] Rouville, "Monographie Geol. de Cabrières, Herault," 1887. Bergeron, "Étude Geol. du Massif ancien au sud du Plateau Central," 1889. Barrois, Ann. Soc. Geol. Nord, xx. 1892, 85. F. Frech, Zeitsch. Deutsch. Geol. Ges. 1887, 360.

Recent researches in the Pyrenees have revealed a great development of fossiliferous rocks which from their graptolites may be paralleled with the English and Scottish Tarannon sub-group.[104] Three zones with Monograptus vomerinus, M. Becki, and M. crassus are well developed, and are compared by Dr. Barrois with the British zones of Rastrites maximus, Monograptus exiguus and Cyrtograptus Grayæ respectively. The same observer remarks that these graptolitic faunas of the Pyrenees present more resemblance with others found in the south of Europe than with those in the original typical regions of Britain and Scandinavia. The specific types are generally the same as those of Bohemia.[105] Silurian rocks have been recognized at various points on the Spanish table-land, a lower quartzite, with Cruziana, Lingula, etc., being surmounted by shales containing Calymene Tristani, etc. Graptolite-bearing schists occur in the province of Minho in the west of Portugal.[106]

Central and Southern Europe.—It is a remarkable fact in the Palæozoic geology of the European continent that while the general facies of the fossils continues tolerably uniform in the northwest and north throughout the Silurian territory first described, that is, from Ireland across the Baltic basin into Russia, a great contrast is to be noted between this northern facies and that of central and southern Europe. The Pyrenean exemplification of the southern type has just been alluded to. But it is in Bohemia that this type is most abundantly developed and most excellently preserved. Out of the many thousands of species obtained in that country very few are found also in the north. Among the forms common to the two regions graptolites are especially prominent, more than a dozen of the characteristic Upper Silurian species of Britain being also found in the southern province.[107]

In the important Silurian basin of Bohemia,[108] so admirably worked out by Barrande, the formations are grouped as in the subjoined table:

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[104] Caralp, "Études geol. sur les hauts Massifs des Pyrenees centrales," Toulouse, 1888, p. 453.

[105] Barrois, Ann. Soc. Geol. Nord, 1892, p. 127. On the Silurian rocks of the Asturias see Barrois, Mem. Soc. Geol. Nord, 1882.

[106] J. F. N. Delgado, Comm. Trabal. Geol. Portugal, II. fasc. ii. 1892.

[107] Marr, Quart. Journ. Geol. Soc. 1880, p. 603.

[108] See Barrande's magnificent work, "Systeme Silurien de la Boheme." F. Katzer, "Geologie von Böhmen," 1892, p. 791. J. E. Marr, Quart. Journ. Geol. Soc. 1880, p. 591.

Upper Silurian.	3d Fauna.	Stage H.[109]	Shales with coaly layers and beds of quartzite (Phacops fecundus, Tentaculites elegans), with species of Leptæna, Orthoceras, Lituites, Goniatites, etc.	850 ft.
		" G.	Argillaceous limestones with chert, shales and calcareous nodules . . . . . . Numerous trilobites of the genera Dalmanites, Bronteus, Phacops, Proëtus, Harpes and Calymene; Atrypa reticularis, Pentamerus linguifer.	1000 "
		" F.	Pale and dark limestone with chert. Harpes, Lichas, Phacops, Atrypa reticularis, Pentamerus galeatus, Favosites gotlandica, F. fibrosa, Tentaculites.	
		" E.	Shales with calcareous nodules and shales resting on sheets of igneous rock (300 ft.), lying with a slight unconformability on the group below . . . . . . A very rich Upper Silurian fauna, abundant cephalopods, trilobites, etc.; Halysites catenularia, graptolites in many species, such as are found in the Birkhill group of Britain.	450–900 "
Lower Silurian.	2d Fauna.	" D.	Yellow, gray and black shales, with quartzite and conglomerate at base, divided by Barrande into five bands numbered Dd1 to Dd5, the first being further separated into three members Dd1 α, β and γ. Dd1 α and β may perhaps be paralleled with the Welsh Tremadoc group, Dd1 γ with the Arenig rocks, Dd 2, 3, 4 and 5 with the Bala-Caradoc rocks . . . . Abundant trilobites of genera Trinucleus, Ogygia, Asaphus, Illænus, Remopleurides, etc.	3000 "
Cambrian.	Primordial Fauna.	" C.	Shales, sometimes with porphyries and conglomerates . . . . Paradoxides, Ellipsocephalus, Agnostus, Arionellus, and other genera of trilobites referred to above (ante, p. 1207).	300 "
		" B.	Grits, shales and conglomerates.	
Pre-Cambrian.		" A.	Green schists, grits, breccias, tuffs and hornstones resting on gneiss.	

Small though the area of the Silurian basin of Bohemia is (for it measures only 100 miles in extreme length by 44 miles in its greatest breadth) it has proved extraordinarily

[109] Stages F, G, H are classed as Devonian by Kayser and other German geologists. (Kayser, Zeitsch. Deutsch. Geol. Ges. xxix. 1877, pp. 207, 629, notices the occurrence of Bohemian Upper Silurian fossils in the Rhenish Lower Devonian rocks.) Barrande defended his classification: Verh. K. Geol. Reichs. 1878, p. 200.

rich in organic remains. Barrande has named and described several thousand species from that basin alone, the greater number being peculiar to it. Some aspects of its organic facies are truly remarkable. One of these is the extraordinary variety and abundance of its straight and curved cephalopods, of which 18 genera and two sub-genera, comprising in all no fewer than 1127 distinct species, were determined by Barrande. The genus Orthoceras alone contained in his census 554 species, and Cyrtoceras had 330.[110] Of the trilobites, which appear in great numbers and in every stage of growth, as many as 42 distinct genera were noted, comprising 350 species; the most prolific genus being Bronteus, which included 46 species entirely confined to the 3d fauna or Upper Silurian. Acidaspis had 40 species, of which six occur in the 2d and 34 in the 3d fauna. Proëtus also numbered 40 species, which all belong to the 3d fauna, save two found in the 2d. Other less prolific but still abundant genera are Dalmanites, Phacops, and Illænus. The 2d fauna, or Lower Silurian series, was found by Barrande to contain in all 32 genera and 127 species of trilobites; while the 3d fauna, or Upper Silurian series, contained 17 genera and 205 species, so that generic types are more abundant in the earlier and specific varieties in the later rocks.[111]

Reference may be made here to the famous doctrine of "Colonies" propounded and ably defended by the illustrious Barrande. Drawing his facts from the Bohemian basin, he believed that while the Silurian strata of that region presented a normal succession of organic remains, there were nevertheless exceptional bands, which, containing the fossils of a higher zone, were yet included on different horizons among inferior portions of the series. He termed these precursory bands "colonies," and defined the phenomena as consisting in the partial co-existence of two general faunas, which, considered as a whole, were nevertheless successive. He supposed that, during the later stages of his second Silurian fauna in Bohemia, the first phases of the third fauna had already appeared, and attained some degree of development, in a neighboring but yet unknown region. At intervals, corresponding doubtless to geographical changes, such as movements of subsidence or elevation, volcanic eruptions, etc., communication was opened be-

[110] "Syst. Silur." ii. suppt. p. 266, 1877.
[111] Op. cit. i. suppt. "Tribolites," 1871.

tween that outer region and the basin of Bohemia. During these intervals, a greater or less number of immigrants succeeded in making their way into the Bohemian area, but as the conditions for their prolonged continuance there were not yet favorable, they soon died out, and the normal fauna of the region resumed its occupancy. The deposits formed during these partial interruptions, notably graptolitic schists and calcareous bands, accompanied by igneous sheets, contain, besides the invading species, remains of some of the indigenous forms. Eventually, however, on the final extinction of the second fauna, and, we may suppose, on the ultimate demolition of the physical barriers hitherto only occasionally and temporarily broken, the third fauna, which had already sent successive colonies into the Bohemian area, now swarmed into it, and peopled it till the close of the Silurian period.[112]

The general verdict of palæontologists has been adverse to this original and ingenious doctrine. The apparent intercalation of younger zones in older groups of rock has been accounted for by such infoldings of strata as have already been described in this work and by the effects of faults. It has been shown that not only are the zones repeated, but that when they reappear they bring with them their minute palæontological subdivisions and their peculiar lithological characters.[113]

Silurian rocks appear in a few detached areas in Germany, but the only comparatively large tract of them occurs in Thuringia and the Fichtelgebirge. They present a great contrast to those of Bohemia in their comparatively unfossiliferous character, and the absence of any one continuous succession of the whole Silurian system. In the Thuringer Wald, a series of fucoidal-slates (perhaps Cambrian) passes up into slates, graywackes, etc., with Lingula, Discina, Calymene, numerous graptolites and other fossils. These strata (from 1600 to 2000 feet thick) may represent the Lower Silurian groups. They are covered by some graptolitic alum-slates, shales, flinty slates, and limestones (Favosites gotlandica, Cardiola interrupta, Tentaculites acuarius, etc.), which no doubt represent the Upper Silurian

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[112] The doctrine of colonies is developed in the "Système Silurien du Centre de la Bohême," 1852, i. p. 73; "Colonies dans le Bassin Silurien de la Bohême," in Bull. Soc. Geol. France (2d ser.) xvii. 1859, p. 602; "Defense des Colonies," Prague, i. 1861, ii. 1862, iii. 1865, iv. 1870, v. 1881.

[113] See J. E. Marr, Q. J. Geol. Soc. 1880, p. 605; 1882, p. 313.

groups, and pass into the base of the Devonian system.[114] The graptolites include many species found in the Stockdale shales of the Lake District, so that the Llandovery group is well represented in this part of the continent.[115] Among the Harz mountains certain graywackes and shales containing land-plants (lycopods, etc.), trilobites (Dalmanites, etc.), graptolites, etc., are regarded as of intermediate age between true Upper Silurian and Lower Devonian rocks.[116]

Among the Alps, the band of ancient sedimentary rocks, which, flanking the crystalline masses of the central chain, has been termed the "graywacke zone," has in recent years been ascertained to contain representatives of the Silurian, Devonian, Carboniferous, and Permian systems.[117] In the eastern Alps, a belt of clay-slate and graywacke, with limestone, dolomite, magnesite, ankerite, and siderite runs from Kitzbühel in the Tyrol as far as the south end of the Vienna basin. About twenty species of fossils (Orthoceras, Atrypa, Cardiola, etc.) found at Tienten, near Werfen, belong apparently to the substage *e*2 of Barrande's Stage E. In this band, the strata have been changed into crystalline schists (p. 1035). As the fossils are Upper Silurian, a large part of the adjacent unfossiliferous schistose rocks may represent older parts of the Silurian system; but no Lower Silurian fossils have yet been found in them in the northern Alps.

In the southern Alps (Carinthia), above the older Palæozoic masses which have not yet yielded fossils, the following subdivisions have been given by Stache in descending order:

Limestones (1000 to 1500 feet) with Silurian forms of Pentamerus, Spirifer, Rhynchonella and Atrypa, and Silurian and Devonian corals=Stages, F, G, H, of Barrande.

Dark clay-slates and sandstones with plant-remains, yel-

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114 Richter, Zeitsch. Deutsch. Geol. Gesell. xxi. p. 359; xxvii. p. 261.

115 Marr, Geol. Mag. 1889, p. 414. Tornquist, Geol. För. Stockholm Förhandl. ix. 1887.

116 Lossen, Zeitsch. Deutsch. Geol. Ges. xx. p. 216; xxii. p. 284; xxix. p. 612.

117 Von Hauer, "Geologie," p. 216. Stache, Jahrb. Geol. Reichsanst. xxiii. p. 175; xxiv. 136, 334; Verh. Geol. Reichs. 1879, p. 216. Stache divided the graywacke zone of the eastern Alps into five pre-triassic groups: 1, Quartzphyllite group; 2, Kalkphyllite group; 3, Kalkthonphyllite group; 4, Group of the older graywackes (Silurian and Devonian); 5, Group of the Upper Coal and Permian rocks.

low and red crinoid-shales=Stage F, in parts Onondago group (?).

Limestone with orthoceratites, gasteropods, lamellibranchs, trilobites (Kokberg). About 100 species occur in the lower or dark Orthoceras limestone. These rocks appear to represent Stage E of Bohemia, and the Ludlow and Wenlock groups of England.

Graptolite-schists with Diplograptus folium, D. pristis, etc.=Stage D and base of E (Tarannon group). Graywacke-slate and sandstone (Strophomena grandis, Orthis)=upper part of Stage D; perhaps Bala beds.[118]

In the southern half of Sardinia, Silurian rocks (in part, at least, Upper) have been divided into three zones, the lowest of which contains important metalliferous lodes.[119] Among these rocks Meneghini recognizes two chief graptolitic horizons, one probably representing the Tarannon subgroup (with Monograptus antennularius, comp. Becki, M. Gonii, comp. continens, M. hemipristis, comp. jaculum) the other (with M. colonus, M. Lamarmoræ, M. multuliferus, comp. vomerinus) answering to the Wenlock group.

In the southwest of Russia (Podolia) and in Gallicia, an Upper Silurian area occurs in which there is almost perfect palæontological agreement with the Silurian rocks of the basin of the Baltic, but a great contrast to those of Bohemia, with which it has only a few brachiopods in common.[120]

North America.[121]—In the United States and Canada, Silurian rocks spread continuously over a vast territory, from the mouth of the St. Lawrence southwestward into Alabama and westward by the great lakes. They almost encircle and certainly underlie all the later Palæozoic deposits of the great interior basin. The rocks are most typically developed in the State of New York, where they have been arranged as in the subjoined table:

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[118] Verhandl. Geol. Reichsanst. 1884, p. 25; Zeitsch. Deustch. Geol. Ges. 1884, p. 277.

[119] Meneghini, Mem. R. Acad. Lincei, 1880.

[120] F. Schmidt, "Die Podolisch-galizische Silurformation," St. Petersburg, 8vo, 1875.

[121] See especially the Memoirs of the Geological Survey of Canada, numerous monographs of Prof. James Hall, of Albany; Walcott, Monogr. U. S. Geol. Surv. viii. 1884.

Upper.

(4) Water-lime (Tentaculites, Eurypterus, and Pterygotus) Onondago salt group, consisting of red and gray marls, sandstones and gypsum, with large impregnation of common salt, but nearly barren of fossils.

(3) Niagara shale and limestone (Halysites, Favosites, Calymene Blumenbachii, Homalonotus delphinocephalus, Leptæna transversalis, etc.); also fish-remains (Onchus, Glyptaspis) in the shale in Pennsylvania. The Niagara Limestone may be paralleled with the Wenlock Limestone.

(2) Clinton group: Pentamerus oblongus, Atrypa reticularis, Monograptus clintonensis, Retiolites venosus, etc. This group may represent the Tarannon shales.

(1) Medina group with Oneida conglomerate (Modiolopsis orthonota).

Lower.

(5) Cincinnati (Hudson River) group: Syringopora, Halysites, Pterinea demissa, Leptæna sericea, Climacograptus bicornis, C. typicalis, Diplograptus pristis, D. putillus. This group corresponds to the Caradoc rocks of Britain.

(4) Utica group--Utica shale: Leptograptus flaccidus, Diplograptus mucronatus (?), D. quadrimucronatus, etc. The shales of Norman's Kiln, near Albany, on the Hudson River, have yielded a large series of graptolites resembling the assemblage that characterizes the Glenkiln shales of Scotland.

(3) Trenton group { Trenton limestone. Black River limestone Birdseye limestone. } Trinucleus concentricus, Orthis testudinaria, Murchisonia, Conularia, Orthoceras, Cyrtoceras, etc.[122]

(2) Chazy group—Chazy limestone: Maclurea magna, M. Logani, Orthoceras, Illænus, Asaphus.

(1) Calciferous group: Lingulella acuminata, Leptæna, Conocardium, Ophileta compacta, Orthoceras primigenium, Amphion, Bathyurus, Asaphus, Conocoryphe, Tetrograptus, Phyllograptus, Didymograptus, Clonograptus, Loganograptus, Diplograptus, etc. This group answers to the Welsh Arenig rocks.[123]

It is interesting to observe the number of genera and even of species common to the Silurian rocks of America and Europe, and the close parallelism in their order of appearance. Not a few of the widely diffused forms occur in Arctic America, so that a former migration along shallow northern waters between the two continents is rendered highly probable. Among these common species the following may be enumerated as occurring in the Upper Silurian rocks of New

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[122] Remains of ganoid fishes, like Holoptychius and Asterolepis, and of a chimæroid fish, have been found in what seems to be a representative of the Trenton group in Colorado. C. D. Walcott, Bull. Geol. Soc. Amer. iii. 1892, p. 153.

[123] According to researches by Mr. Selwyn, the so-called Quebec group as defined by Logan embraces three totally distinct groups of rock, belonging respectively to Archæan, Cambrian and Lower Silurian horizons; and in the fossiliferous belt of Logan's Quebec group are included—in a folded, crumpled and faulted condition—portions of subdivisions that lie elsewhere comparatively undisturbed, and embrace strata even lower than the Potsdam formation. Trans. Roy. Soc. Canada, vol. i. sect. iv. p. 1, 1882.

York, the coasts of Barrow Straits within the Arctic Circle, Britain, and the Baltic basin: Stromatopora concentrica, Halysites catenularia, Favosites gotlandica, Orthis elegantula, Atrypa reticularis. The genera of graptolites appear to have followed the same order of appearance and to have reached their full development and final decline at corresponding stages of the Silurian period on each side of the Atlantic. Among the crustacea, trilobites were the dominant order, represented in each region by a similar succession of genera, and even to some extent of species. And as these earlier forms of articulates waned, there appeared among them about the same epoch in the geological series, the eurypterids of the Water-lime of New York and of the Ludlow rocks of Shropshire and Lanarkshire.

Asia.—Silurian rocks have been recognized over a large part of the surface of the globe. They have been found, for example, running through the Cordilleras of South America on the one hand, and among the older rocks of the Himalaya chain on the other. The Salt Range of the Punjab contains thick masses of bright red marl, with beds of rock-salt, gypsum and dolomite, over which lie purple sandstones and shales. These saliferous rocks have been already (p. 1230) referred to as containing Cambrian fossils, but it is not yet known whether they include any representatives of the Silurian system.[124] In the regions of the Northern Punjab and Kashmir traces of Silurian organic remains have been discovered; while in the north of Kumaun such fossils have been found in considerable quantities.

From the province of Sze Chuen, in Western China, Richthofen has obtained numerous fossils which show the presence there of Middle and Upper Silurian rocks. Among the species, some are the same as those that occur in Western Europe, such as Orthis calligramma, Laptæna sericea, Spirifer radiatus, Atrypa reticularis, Favosites fibrosa, Heliolites interstinctus, Halysites catenularia, and others.[125]

Australasia.—In Australia the existence of the Silurian system has been proved by the discovery of a considerable number of characteristic fossils, among which are numerous

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[124] A. B. Wynne, Mem. Geol. Surv. India, xiv. See also Palæont. Indica. ser. 13, vol. i. 1887, p. 750; Medlicott and Blanford, "Manual of the Geology of India," 1879.

[125] Richthofen's "China," vol. iv. pp. 37, 50, where descriptions of the fossils are given by Kayser and Lindström.

graptolites of the genera Climacograptus, Cœnograptus, Dichograptus, Dicranograptus, Didymograptus, Diplograptus, Monograptus, Loganograptus, Phyllograptus, Retiolites, and Tetragraptus, with species of Siphonotreta and Hymenocaris, which occur in the Lower Silurian series of Victoria—an enormous series of sedimentary deposits, estimated by Mr. Selwyn to be not less than 35,000 feet thick—also many Upper Silurian fossils from New South Wales and Victoria, including such world-wide species as Favosites gotlandica, Heliolites interstinctus, Calymene Blumenbachii, Encrinurus punctatus, Entomis tuberosa, Phacops caudatus, Atrypa reticularis, Strophomena pecten, Pentamerus Knightii, P. oblongus, Whitfieldia (Meristella) tumida, Orthoceras ibex.[126] Near Bathurst and elsewhere, the Upper Silurian rocks of New South Wales have been much altered, sandstones passing into quartzites, slates into gneiss and hornblendic schists, and the coral-limestones into crystalline marbles with total obliteration of fossils.[127]

In New Zealand some dark slates and crystalline limestones which form the mass of Mount Arthur, and from which a few graptolites, etc., have been obtained, are referred to the Lower Silurian series. They are much disturbed by hornblendic and syenitic eruptive rocks. To the Upper Silurian series are assigned some fossiliferous rocks from which Calymene Blumenbachii, Spirifer radiatus, Stricklandinia lyrata, etc., have been procured (Baton River series). A great part of the so-called metamorphic schists are probably Upper Silurian rocks.[128]

Section iii. Devonian and Old Red Sandstone

In Wales and the adjoining counties of England, where the typical development of the Silurian system was worked out by Murchison, the abundant Silurian marine fauna disappears in the red rocks that overlie the Ludlow group. From that horizon upward in the geological series, we have

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[126] McCoy, "Prodromus of Palæontology of Victoria"; L. G. de Koninck, "Recherches sur les Fossiles Paléozoiques de la Nouvelle-Galles du Sud," Brussels, 1876; R. Etheridge, jun., "Catalogue of Australian Fossils"; W. B. Clarke, "Remarks on the Sedimentary Formations of New South Wales," 4th edit.; C. S. Wilkinson, "Notes on the Geology of New South Wales," Sydney, 1882.

[127] C. S. Wilkinson, op. cit.

[128] Hector, "Handbook of New Zealand," p. 37.

to pass through some 10,000 feet or more of barren red sandstones and marls, until we again encounter a copious marine fauna in the Carboniferous Limestone. It is evident that between the disappearance of the Silurian and the arrival of the Carboniferous fauna, very great geographical changes occurred over the site of Wales and the west of England. For a prolonged period, the sea must have been excluded, or at least must have been rendered unfit for the existence and development of marine life, over the area in question. The striking contrast in general facies between the organisms in the Silurian and those in the Carboniferous system, proves how long the interval between them must have been.

The geological records of this interval are still only partially unravelled and interpreted. At present the general belief among geologists is that, while in the west and north of Europe the Silurian sea-bed was upraised into land in such a way as to inclose large inland basins, in the centre and southwest the geographical changes did not suffice to exclude the sea, which continued to cover that region more or less completely. In the isolated basins of the west and north, a peculiar type of deposits, termed the Old Red Sandstone, is believed to have accumulated, while in the shallow seas to the south and east, a series of marine sediments and limestones was formed, to which the name of Devonian has been given. It is thus supposed that the Old Red Sandstone and Devonian rocks represent different geographical areas, with different phases of sedimentation and of life, during the long lapse of time between the Silurian and Carboniferous periods. A somewhat similar contrast between the lithological and palæontological characters of the corresponding formations in different parts of the United States and Canada, shows that in America also this geological period was

marked by geological changes which produced distinct geographical conditions in adjacent regions.

That the Old Red Sandstone of Britain does represent the prolonged interval between Silurian and Carboniferous time can be demonstrated by innumerable sections, where the lowest strata of the system are found graduating downward into the top of the Ludlow group, and where its highest beds are seen to pass up into the base of the Carboniferous system. But the evidence is not everywhere so clear in regard to the true position of the Devonian rocks. That these rocks lie between Silurian and Carboniferous formations was long ago shown by Lonsdale from their fossils. But it is a curious fact that where the Lower Devonian beds are best developed, the Upper Silurian formations are scarcely to be recognized, or, if they occur, can hardly be separated from the so-called Devonian rocks. It is quite possible, therefore, that the lower portions of what has been termed the Devonian series may, in certain regions, to some extent represent what are elsewhere recognized as undoubted Ludlow or even perhaps Wenlock rocks.[129] We cannot suppose that the rich Silurian fauna died out abruptly at the close of the Ludlow epoch. We should be prepared for the discovery of Silurian rocks younger than the latest of those in Britain, such as Barrande showed to exist in his Etage H, or for a Devonian facies of fossils in rocks which are nevertheless regarded as Silurian. The rocks termed Lower Devonian may partly represent some of the later phases of Silurian life. On the other

[129] According to Kayser and Beyrich the limestones of the Hercynian series in the Harz and Nassau, together with Barrande's Upper Silurian Stages F, G, H, in Bohemia, are to be regarded as truly Devonian, and as being the deeper water equivalents of the arenaceous series of the normal Lower Devonian series on the Rhine. (Abhandl. Geol. Specialkarte Preussen, II. Heft 4, 1878. Zeitsch. Deutsch. Geol. Ges. xxxiii. 1881, p. 628.)

hand, the upper parts of the Devonian system might in several respects be claimed as fairly belonging to the Carboniferous system above.

J. B. Jukes proposed a solution of the Devonian problem, the effect of which would be to turn the whole of the Devonian rocks into Lower Carboniferous, and to place them above the Old Red Sandstone, which would thus become the sole representative in Europe of the interval between Silurian and Carboniferous time.[130] In the following descriptions an account will first be given of the Devonian type and then of the Old Red Sandstone.

I. DEVONIAN TYPE

§ 1. General Characters

ROCKS.—Throughout central and western Europe, the Devonian system presents a remarkable persistence of petrographical characters, indicating probably the prevalence of the same kind of physical conditions over the area during the period when the rocks were accumulated. The lower division consists mainly of sandstones, grits, and graywackes, with slates and phyllites. These rocks attain a great development on the Rhine, where they form the material through which the picturesque gorges of the river have been eroded. In the central zone, limestones predominate, often crowded with the corals and mollusks of

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[130] See his papers in Journ. Roy. Geol. Soc. Ireland, 1865, i. pt. 1, new ser., and Quart. Journ. Geol. Soc. xxii. 1866, and his pamphlet on "Additional Notes on Rocks of North Devon," etc. 1867. The "Devonian question," as it has been called, has evoked a large number of papers, of which, besides those cited in subsequent pages, the following may be enumerated: Prof. Hull, Q. J. Geol. Soc. xxxv. 1879, p. 699; xxxvi. 1880, p. 255. A. Champernowne, Geol. Mag. v. 2d Ser. 1878, p. 193; vi. 1879, p. 125; viii. 1881, p. 410. The general verdict has been adverse to the explanation of the structure of North Devon proposed by Jukes.

the clearer water in which they were laid down, and in some cases actually representing former coal-reefs.[131] The upper series is more variable: being in some tracts composed of sandstones and shales, in others of shales and limestones, but everywhere presenting a more shaly thin-bedded aspect than the subdivisions beneath it. Considerable masses of diabase, tuff (schalstein), and other associated volcanic material are intercalated in the Devonian system in Devonshire and in Germany. As a rule, the rocks have been subjected to more or less disturbance, and have in some places been plicated and cleaved, and even metamorphosed into schists, quartzites, etc. In some districts, they have been invaded by large masses of granite and other eruptive rocks.

Among the economic products, the most important in Europe are the ores of iron, lead, tin, copper, etc., which occur in veins or lenticular masses through the Devonian rocks (Devon and Cornwall, Harz, etc.). In North America the Devonian rocks of Pennsylvania contain bands of "sand-rock" charged with petroleum.

LIFE.—An abundant cryptogamic flora covered the land during the ages that succeeded the Silurian period. As the remains of this vegetation are chiefly preserved in the Old Red Sandstone facies of deposits, it is described at p. 1316. But the true Devonian rocks contain remains of marine vegetation, of which Haliserites is a frequent seaweed in the Lower Devonian rocks of the Rhine. The fauna of the Devonian rocks is unequivocally marine. Among the more

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[131] Dupont, Bull. Acad. Roy. Belgique (3) ii.; Comptes Rend. Feb. 18, 1884. The frequent singularly lenticular character of Palæozoic limestones is explicable on the assumption that in many cases they grew up in patches after the manner of modern coral-reefs. The interrupted bands of shale in the Belgian Devonian limestones are regarded by M. Dupont as representing the lagoons that were filled up with muddy sediment.

lowly forms of life are some of which the true zoological grade has been the subject of much uncertainty. Of these, the fossil known as Calceola sandalina (Fig. 349) has been successively described as a lamellibranch, a hippurite, and a brachiopod; but is now regarded as a rugose coral possessing an opercular lid. The Pleurodictyum problematicom, a well-known form of the Lower Devonian beds, is now classed with the Favositidæ among the perforate corals. The puzzling genus Stromatopora occurs in some of the limestones as abundantly and much in the same way as reef-building corals do in a modern coral-reef. The curious Receptaculites, already (p. 1235) referred to, is a well-known Devonian fossil. The last graptolites are met with in the Devonian system. They are of the simple type so characteristic of the Upper Silurian rocks, and have chiefly been found in the Hercynian formation of the Harz.[132] The corals of the Devonian seas were both abundant in individuals and varied in their specific and generic range. Not a single species is common either to the Silurian system below or the Carboniferous above. Among the rugose forms, the genera Cyathophyllum, Acervularia, and Cystiphyllum are characteristic. The tabulate kinds belong chiefly to the important genera of Favosites, Alveolites, and Heliolites. Calceola and Pleurodictyum, already referred to, are important Lower Devonian corals, while Phillipsastræa is of great consequence among the coral-reefs of the Upper Devonian rocks. Of the echinoderms by far the most abundant representatives are crinoids, which occur in great profusion in the limestones, sometimes forming entire beds of rock. They belong chiefly to two families—the Cyathocrinidæ, simple pedunculate forms with

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[132] E. Kayser, Abhandl. Specialkarte Preussen, II. Heft 4, 1878.

five branching arms, and Cupressocrinidæ (wholly Devonian) having five arms which when folded up form a pentagonal pyramid, the accurate fitting of which recalls the ambulacra

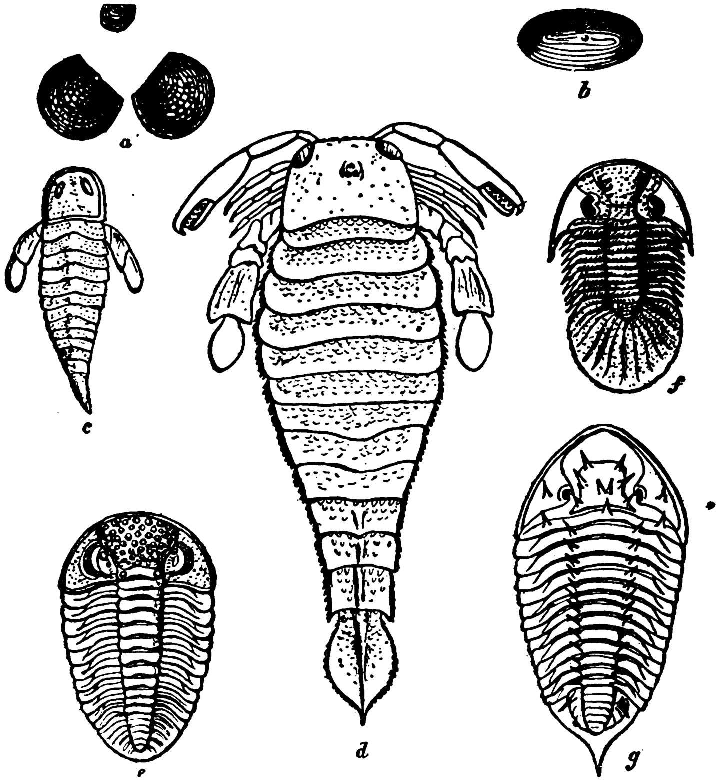

Fig. 348.—Devonian and Old Red Sandstone Crustacea.

a, Estheria membranacea, Pacht., nat. size and magnified (Lower Old Red Sandstone); *b*, Entomis (Cypridina) serrato-striata, Sandb., magnified (Upper Devonian); *c*, Eurypterus pygmæus, Salt. (Lower Old Red Sandstone); *d*, Pterygotus anglicus, Ag. (Lower Old Red Sandstone); *e*, Phacops latifrons, Bronn. (Lower Devonian); *f*, Bronteus flabellifer, Goldf. (Lower Devonian); *g*, Homalonotus armatus, Burm. (Lower Devonian).

of sea-urchins. The Cystideans appear to have died out in the Devonian period. True star-fishes also occur (Helianthaster, Astropecten, Cœlaster).

The known crustacean fauna of the Devonian period

indicates a striking diminution in number both of individuals and of species of trilobites (Fig. 348). Most of the genera so abundant and characteristic among the Silurian rocks are now absent, the most frequent Devonian forms being species of Phacops, Cryphæus, Dalmanites, Homalo-

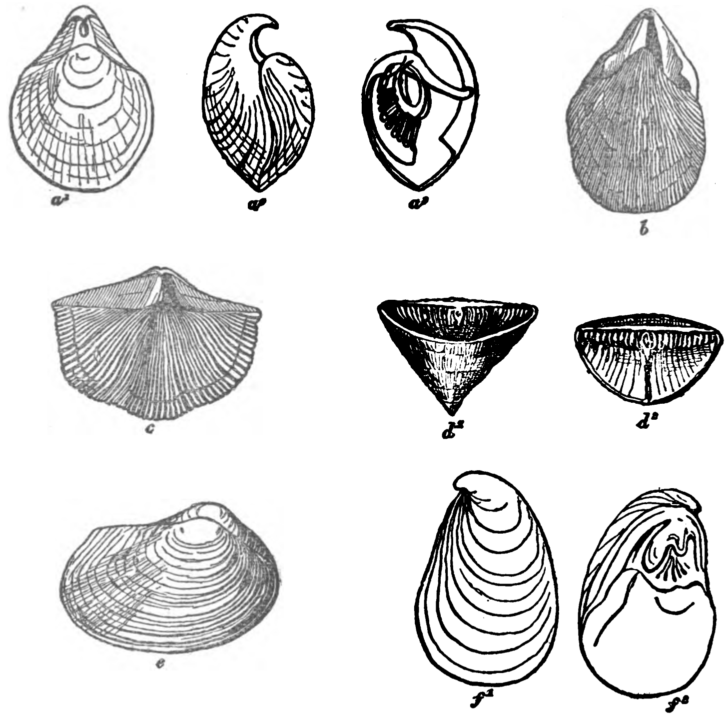

Fig. 349.—Devonian Fossils.
a1, Stringocephalus Burtini, Def.; *a2*, Do. lateral, and *a3*, Do. internal view; *b*, Uncites gryphus, Def.; *c*, Spirifer Verneuili (disjunctus), Sow.; *d1*, Calceola sandalina, Linn.; *d2*, Opercular lid of do.; *e*, Cucullæa Hardingii Sow.; *f1*, *f2*, Megalodon cucullatus, Sow.

notus, and Bronteus. But some other Silurian genera still survived, especially Acidaspis, Calymene, Cheirurus, Harpes, Lichas, and Proëtus. The ostracods are chiefly represented by the genus Entomis (Cypridina), which occurs in enormous numbers in some Upper Devonian shales

("Cypridinen-schiefer"). The phyllopods, eurypterids, and myriapods appear chiefly in the Old Red Sandstone, and are noticed on p. 1318 (Fig. 348, *a*, *c*, *d*).

Among the mollusca of the Devonian rocks remains of the pteropod Tentaculites are not uncommon. The brachiopods (Fig. 349) now reached perhaps their maximum development, whether as regards individual abundance or number of specific and generic forms; more than 60 genera and 1100 species having been described. They compose three-fourths of the known Devonian fauna. While all the families of the class are represented, the most abundant are the Spiriferidæ, including the genera Spirifer (especially broad-winged species), Cyrtia, Athyris (Spirigera), Uncites and Atrypa (A. recticularis ranging from the Upper Silurian through the Devonian system), and the Rhynchonellidæ (Rhynchonella, Camarophoria, Pentamerus). The Strophomenids or Orthids, so abundant in the Silurian rocks, are now represented by a waning number of forms, including the genera Orthis, Strophomena, Streptorhynchus and Leptæna. The Productids made their appearance in Silurian times, but were more abundant in the Devonian seas, where their most frequent genera were Chonetes and Productus, both of which attained their maximum development in the Carboniferous period. One of the most characteristic and largest Devonian brachiopods is Stringocephalus—a genus allied to Terebratula, but entirely confined to this geological system (Fig. 349, *a*). Another characteristic terebratula-like form is Rensseleria.

The known Devonian lamellibranchs belong chiefly to the genera Pterinea, Cardiola, Megalodon, Grammysia, Cucullæa, Curtonotus, Lucina, and Aviculopecten; Pterinea being specially abundant in the lower, Cucullæa and Curto-

notus in the upper subdivision of the system. The most important genera of gasteropods are Euomphalus, Murchisonia, Loxonema, Macrocheilus, Acroculia (Capulus) and Pleurotomaria, with the heteropods Bellerophon and Porcellia. The cephalopods embrace representatives of both the tetrabranchiate families of Nautilids and Ammonitids. Among the Nautilids are the genera Clymenia, an especially abundant form in some of the Upper Devonian shales and limestones, Gyroceras, Orthoceras, Cyrtoceras, Hercoceras, and Gomphoceras. The great family of the Ammonites had, in the Devonian waters, representatives of the more abundant coiled forms, in the characteristic genus Goniatites, and of the straight forms, in Bactrites. Other Devonian genera are Anarcestes, Aphyllites, Beloceras, Gephyroceras, Mimoceras, Pinacites, Prolecanites, Sporadoceras, and Tornoceras. In the Devonian rocks of central Europe, scanty remains of the great fish fauna of the Old Red Sandstone have been found, more especially in the Eifel, but seldom in such a state of preservation as to warrant their being assigned to any definite place in the zoological scale. Prof. Beyrich has described from Gerolstein in the Eifel an undoubted species of Pterichthys, which, as it cannot be certainly identified with any known form, he has named P. rhenanus. A Coccosteus has been described by F. A. Roemer from the Harz, and more recently one has been cited from Bicken near Herborn by Von Koenen; but, as Beyrich points out, there may be some doubt as to whether the latter is not a Pterichthys.[133] A Ctenacanthus, seemingly indistinguishable from the C. bohemicus of Barrande's Etage G, has also been obtained from the Lower Devonian "Nereitenschichten" of Thuringia.[134] Two sharks

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[133] Zeitsch. Deutsch. Geol. Gesell. xxix. 751. [134] Op. cit. 423.

(Palædaphus devoniensis and Byssacanthus Gosseleti) have been obtained from the Belgian and north of France area. The characteristic Holoptychius nobilissimus has been detected in the Psammite de Condroz, which in Belgium forms a characteristic sandy portion of the Upper Devonian rocks. These are interesting facts, as helping to link the Devonian and Old Red Sandstone types together. But they are as yet too few and unsupported to warrant any large deduction as to stratigraphical correlations between these types. The fishes of the Old Red Sandstone are noticed on p. 1320.

§ 2. Local Development

Britain.[135]—The name "Devonian" was first applied by Sedgwick and Murchison to the rocks of North and South Devon and Cornwall, whence a suite of fossils was obtained which Lonsdale pronounced to be intermediate in character between Silurian and Carboniferous. The passage of these strata into Silurian rocks has not been satisfactorily determined,[136] but they clearly graduate upward into Carboniferous strata. Considerable difference exists between the development of the Devonian rocks in the north and south of Devonshire. In the former area they consist of sandy and muddy materials in the form of sandstones, grits, and slates. In South Devonshire on the other hand they in-

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[135] Sedgwick and Murchison, Trans. Geol. Soc. 2d ser. v. p. 633. Sedgwick, Q. J. Geol. Soc. viii. p. 1. Lonsdale, Proc. Geol. Soc. iii. p. 281. R. A. Godwin-Austen, Trans. Geol. Soc. (2) vi. p. 433. J. W. Salter, Q. J. Geol. Soc. xix. p. 474. T. M. Hall, op. cit. xxiii. p. 371. Etheridge, Q. J. Geol. Soc. xxiii. 1867, 568, where a copious bibliography up to date will be found; also op. cit. xxxvii. Address, p. 178. A. Champernowne and W. A. E. Ussher, Q. J. Geol. Soc. 1879, p. 532. A. Champernowne, op. cit. 1889, p. 369. W. A. E. Ussher, Geol. Mag. 1881, p. 441, Quart. Journ. Geol. Soc. 1890, p. 487. E. Kayser, Neues Jahrb. 1889, i. p. 189. The Devonian rocks of Cornwall and Devon have undergone much crumpling and have suffered considerable metamorphism. Their fossils are often singularly distorted, and mica has been almost everywhere abundantly developed in their argillaceous and calcareous portions. Much of the so-called "slate" or "killas" of these districts is a lustrous phyllite. On distortion of the fossils, see D. Sharpe, Q. J. Geol. Soc. iii.

[136] The recent discovery by Mr. Fox and Mr. Teall of radiolarian cherts at the Lizard in Cornwall, and the tracing of these cherts eastward into the Silurian tract of Gorran may furnish a base-line for determining the relations of Silurian and Devonian rocks in the southwest of England.

clude thick masses of limestone and abundant volcanic intercalations in the form of tuffs (schalstein) and lavas (diabase, etc.). With these lithological contrasts there is a corresponding difference in the abundance and variety of organic remains, the calcareous rocks of Plymouth and Torquay being the chief repositories of fossils. Yet even at the best the Devonian rocks of this classical region, though they served as the type formations of the same geological age elsewhere, are much less clearly and fully developed than those of the Rhine country and other parts of the Continent. It is rather from the sections and fossil collections of central Europe than from those of England that the stratigraphy and palæontology of the Devonian system are to be determined.

This system has long been grouped into three divisions, each more or less distinctly marked off by its palæontological characters. In Devonshire and West Somerset these divisions are arranged as follows:

	Northern Type	Southern Type
UPPER.	Pilton group. Slates and grits with calcareous seams: Spirifer Verneuili, Athyris concentrica, Productus prælongus, etc. Baggy group. Sandstones with Cucullæa, slates with Lingula, Discina. Pickwell-Down group. Red, green, gray and purple slates and grits, generally unfossiliferous. Morte slates, unfossiliferous, passing down into the slates below.	Slate near Ashburton with Spirifer Verneuili, etc. Slates of Livaton with Clymenia. Red and green slates with Posidonia venusta and abundant Entomis (Cypridina) serratostriata (= Cypridinen-schiefer). Red and gray slates with volcanic tuffs. Chudleigh limestone with Goniatites intumescens, G. lobatus, G. acutus, G. simplex, Cardiola retrostriata, Rhynchonella cuboides, R. acuminata, Atrypa reticularis, Spirifer bifidus, Productus subaculeatus, etc.
MIDDLE.	Ilfracombe slates; gray silvery slates with lenticular impure fossiliferous limestone, resting on grits and slates of Combe Martin (Cyathophyllum cespitosum, etc.)	Torquay and Plymouth limestones passing laterally into slates and volcanic rocks: Stringocephalus Burtini, Uncites gryphus, Favosites polymorpha, etc. Slates and limestones of Hope's Nose: Atrypa reticularis, Kayseria lens, Spirifer speciosus, S. curvatus, Rhynchonella procuboides, etc. = Calceola beds.
LOWER.	Hangman grits and slates (Natica, Myalina). Lynton group, grits and calcareous slates: Spirifer hystericus, Chonetes sarcinalatus, etc. Foreland grits and slates.	Slates and graywackes (Cockington, Warberry, Meadfoot) with Pleurodictyum problematicum, Homalonotus, Spirifer cultrijugatus, S. hystericus, Pterinea costata, etc.

Lower.—The clay-slate of Looe, Cornwall, has yielded a species of Pteraspis, also Pleurodictyum problematicum. The lower gritty slates and limestone bands of North Devon contain, among other fossils, Favosites (Pachypora) cervicornis, Cyathophyllum helianthoides, Petraia celtica, Pleurodictyum problematicum, Cyathocrinus (two species), Homalonotus (two species), Phacops laciniatus, Fenestella antiqua, Atrypa reticularis, Orthis arcuata, Spirifer canaliferus, S. lævicostus, Pterinea spinosa, etc. The recent researches of Mr. Ussher and Prof. Kayser have brought the Lower Devonian rocks of South Devon into closer palæontological relations with their equivalents on the Continent. Among the species noted by these observers are—Pleurodictyum problematicum, Spirifer hystericus, S. paradoxus, S. macropterus, S. cultrijugatus, Strophomena rhomboidalis, Rhynchonella daleidensis, Chonetes sarcinulata, C. semiradiata, Pterinea costata, Homalonotus gigas—an assemblage which resembles that in the Coblenzian stage of Rhineland.

Middle.—It is in this division that limestones are best developed and fossils are most abundant. Some of the limestones of South Devon are made up of corals, and from their lenticular or sporadic occurrence suggest that they were accumulated as reefs. Large masses of limestone rapidly die out laterally and are replaced by slates. In the Ashprington district a thick group of volcanic rocks consisting of breccias and tuffs (schalstein) and diabasic lavas appears entirely to take the place of the limestones. These volcanic ejections are traceable for many miles, sometimes dwindling down and giving place to limestones or slates, and again swelling out into considerable masses.[137] They appear to have been discharged from numerous small vents across the area of south Devonshire, but no trace of any similar material has yet been detected in the northern part of the county.

The palæontological evidence makes it abundantly clear that the limestones of Torquay and Plymouth represent the great Middle Devonian limestones of France, Belgium, and Germany—the Calcaire de Givet, and the Stringocephalen-Kalk and Calceola-Kalk of the Eifel. Near Torquay shaly limestones occur containing fossils that place them on the

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[137] Champernowne on the Ashprington Volcanic Series, Quart. Journ. Geol. Soc. 1889, p. 369.

horizon of the Eifelian group or the Calceola beds of the Continent, that is, the lower division of the Middle Devonian rocks. Among these fossils are Atrypa reticularis, A. aspera, A. desquamata, Kayseria lens, Leptæna interstrialis, Pentamerus galeatus, Rhynchonella procuboides, Spirifer curvatus, S. speciosus, Streptorhynchus umbraculum, Productus subaculeatus, Phacops latifrons, Cyathophyllum heterophyllum, C. damnoniense, C. helianthoides, Cystiphyllum vesiculosum, Calceola sandalina, Favosites Goldfussi, Heliolites porosa, Stromatopora concentrica. The massive limestones yield the characteristic fauna of the Givet or Stringocephalus limestone, including the corals Cyathophyllum helianthoides, C. damnoniense, Cystiphyllum vesiculosum, Alveolites, Favosites polymorpha, Striatopora denticulata, Amphipora ramosa, Heliolites porosa, Favosites Goldfussi, Stromatopora, Receptaculites Neptuni, Stringocephalus Burtini, Uncites gryphus, Terebratula Whidbornei, T. juvenis, Cyrtina heteroclita, Spirifer undiferus, Rhynchonella parallelopipeda, R. procuboides, R. pugnus, R. lummatoniensis, Pentamerus brevirostris, Leptæna interstrialis, Productus subaculeatus, Cypricardinia, Proëtus, Bronteus, etc.[138]

Upper.—In South Devon, Upper Devonian rocks are now known to be well developed and to present palæontological representatives of the several zones which have been established in this division on the Continent. Three such zones have been recognized. 1st, Massive limestones which pass down continuously into those of Middle Devonian age. They contain Rhynchonella cuboides, R. acuminata, Atrypa reticularis, Athyris concentrica, Spirifer bifidus, S. lineatus, Productus subaculeatus, Waldheimia Whidbornei, Merista plebeia, Conocardium, Harpes, Stromatopora Hüpschii, Actinostroma clathratum (?), etc. 2d, Goniatite beds which, overlying and passing down into the limestones, are marked by the presence of numerous goniatites (G. intumescens, G. complanatus, G. multilobatus, G. acutus, G. simplex), with Cardiola retrostriata, Myalina sp., Sanguinolaria, Bactrites, Alveolites. 3d, Cypridina-slates, containing ostracods (Entomis or Cypridina serratostriata) and Clymenias (C. lævigata and other species). These three zones may be paralleled respectively with the Frasnien and Fammenien group of the Franco-Belgian area and with the

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[138] Ussher, Quart. Journ. Geol. Soc. 1890, p. 501. E. Kayser, Neues Jahrb. 1889, i. p. 185.

Goniatite (Adorf, Iberg) limestone, Cypridina slates and Clymenia limestone of the Eifel and Rhine.

In North Devon this palæontological grouping has not been so satisfactorily made out; but in that region there is an insensible gradation upward through various sandy and muddy sediments into the Culm or Carboniferous system. The micaceous flaggy sandstones of Baggy Point contain Cucullæa trapezium, C. Hardingii, Avicula damnoniensis, Lingula squamiformis, Discina, Rhynchonella laticosta, Strophalosia productoides, Spirifer disjunctus, etc. The greenish slates and calcareous bands of Pilton near Barnstaple have yielded some characteristic fossils of the uppermost part of the Devonian system, such as Petraia celtica, Cyathocrinus pinnatus, Spirifer Verneuili, Athyris concentrica, Streptorhynchus crenistria, Productus prælongus, Strophalosia productoides, S. caperata, Rhynchonella pleurodon, and Chonetes hardrensis. Remains of land-plants are found in the Upper Devonian rocks of North Devon: Sagenaria (Knorria) veltheimiana, Archæopteris (Palæopteris) hibernica. The higher red and yellow sandy portions of these rocks shade up insensibly at Barnstaple in North Devon into strata which by their fossils are placed at the base of the Carboniferous Limestone series. But in no other British locality save in Devonshire can such a passage be observed. In all other places, the Carboniferous system, where its true base can be seen, passes down into the red sandy and marly strata of the Upper Old Red Sandstone without marine fossils.

Central Europe.—A large tract of Devonian rocks extends across the heart of Europe from the north of France through the Ardennes, the south of Belgium, Rhenish Prussia, Westphalia and Nassau. But that the same rocks have a much wider spread under younger formations which cover them is shown by their reappearance far to the west in Brittany,[139] and to the east in the Harz and the Thuringer Wald. They present a much clearer sequence of strata than their British equivalents, for they can be seen in many places to pass down into Silurian strata as well as to graduate upward into the Carboniferous system. In the Belgian and Eifelian tracts they have been subdivided as shown on page 1305.

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[139] A ridge of Devonian rocks stretches eastward under the south of England (where its existence has been proved by well-borings at London), and no doubt joins the Devonian area of the Boulonnais.

	Belgium and the North of France.[140]	Rhineland.[141]
UPPER.	**Famennien**, consisting of two facies, one sandy, the other shaly. (*b*) Psammites du Condros (Condrusien), in which six zones are distinguished (*Cucullæa Hardingii, Spirifer Verneuili, Rhynchonella Dumonti, Orthis crenistria, Phacops latifrons, Archæopteris hibernica, Sphenopteris flaccida*, &c. (*a*) Schistes de Famenne, divisible into four zones (1) that of *Spirifer distans*, (2) of *Rhynchonella letiensis*, (3) of *Rhynchonella Dumonti*, (4) of *Rhynchonella Omaliusi*. **Frasnien**, varying in composition and organic contents in different parts of the Devonian basins. In the Dinant basin it consists of (*b*) Schistes de Matagne (*Goniatites retrorsus, Cardium palmatum, Camarophoria tumida, Bactrites subconicus, Entomis* [*Cypridina*] *serrato-striata*). (*a*) Calcaires et schistes de Frasne, shales and lenticular limestones, sometimes of great thickness, with abundant fossils (*Bronteus flabellifer, Goniatites intumescens, Spirifer Verneuili, Sp. pachyrhynchus, Sp. orbelianus, Spirigera concentrica, Atrypa reticularis, Rhynchonella cuboides, Pentamerus brevirostris, Camarophoria formosa, Receptaculites Neptuni*).	Younger group of Cypridina shales, with *Entomis* (*Cypridina*) *serratostriata, Avicula* (*Posidonia*) *venusta, Phacops cryptophthalmus*, and limestones (Kramenzelkalk) with numerous Clymenias (*C. lævigata, C. undulata, C. striata*, &c.), and Goniatites. Brachiopod limestone directly overlying the Middle Devonian limestone, and containing *Rhynchonella cuboides, R. pugnus, R. acuminata, Spirifer Verneuili, Camarophoria formosa, Productus subaculeatus, Goniatites intumescens*. Iberg limestone of Harz, Adorf limestone of Waldeck, shales of Büdesheim in the Eifel, with *Goniatites intumescens, Rhynchonella cuboides*, and *Cardiola retrostriata*. The prevalence of this Rhynchonella has led to the group being called the "Cuboides beds," and the Goniatite has given the name of "Intumescens beds."
MIDDLE.	**Givetien.**—The great limestone of the middle Devonian series, well seen at Givet, above Dinant on the Meuse, 400 metres thick. Among the abundant characteristic fossils are *Spirifer mediotextus, Sp. undiferus, Stringocephalus Burtini, Uncites gryphus, Megalodon cucullatus, Murchisonia coronata, M. bilineata, Cyathophyllum quadrigeminum, Heliolites porosa*. In the basin of Namur the conglomerate of Pairy-Bony lies below the limestone, and contains a band of sandstone with plants (*Lepidodendron gaspianum*). **Eifélien**, Shales (Schistes de Couvin), with *Calceola sandalina, Phacops latifrons, Bronteus flabellifer, Spirifer curvatus, Sp. subcuspidatus, Sp. elegans, Spirigera concentrica, Pentamerus galeatus, Strophalosia productoides*, &c.	(*b*) Stringocephalus group, consisting of the great Eifel limestone with underlying crinoidal beds (*Stringocephalus Burtini, Uncites gryphus, Spirifer undatus, Productus subaculeatus, Pentamerus galeatus, Atrypa reticularis, Macrocheilus arculatus, Pleurotomaria delphinuloides, Murchisonia bilineata, Megalodon cucullatum*, and many corals and crinoids). (*a*) Calceola group,—marly limestones with *Athyris concentrica, Camarophoria microrhyncha, Atrypa reticularis, Merista plebeia, Spirifer speciosus, S. curvatus, Pentamerus galeatus, Rhynchonella parallelopipeda, Orthis striatula, Calceola sandalina, Cyathophyllum heliantoides, Cystiphyllum vesiculosum, Heliolites porosa, Alveolites, Favosites, Stromatopora, Phacops Schlotheimi*, &c., resting upon impure shaly ferruginous limestone and greywacke, marked by an abundance of *Spirifer cultrijugatus, Rhynchonella orbignyana, Atrypa reticularis, Phacops latifrons*, &c.
LOWER.	**Coblenzien**, composed of greywacke, sandstones, shales, and conglomerate, having a united thickness of sometimes 7000 or 8000 feet, and divisible into five sub-groups as under:— 5. Greywacke of Hierges with (*b*) Zone of *Spirifer cultrijugatus, Calceola sandalina*. (*a*) Zone of *Spirifer arduennensis, Pterinea lineata*. 4. Red slates of Vireux and conglomerate of Burnot. 3. Black sandstone of Vireux (Ahrien). 2. Greywacke of Montigny with *Spirifer paradoxus, Athyris undata, Strophomena depressa* (Hundsrückien). 1. Sandstone of Anor (Taunusien). **Gedinnien**, comprising an upper group of shales and sandstones and a lower group of fossiliferous shales, quartzo-phyllades, quartzites, and conglomerates. The fossils in the lower group comprise *Dalmanites, Homalonotus Roemeri, Primitia Jonesii, Tentaculites grandis, T. irregularis, Spirifer Mercuri, Orthis Verneuili, Pterinea ovalis*, &c. The base of the Devonian system lies unconformably on Cambrian rocks.	Coblenz group (Spirifer sandstone) divisible into the three following sub-groups:— (*c*) Upper greywacke and slate (Coblenz, Ems, Daleiden) with *Ctenocrinus decadactylus, Spirifer auriculatus, S. curvatus, S. paradoxus, Atrypa reticularis, Chonetes dilatata, Homalonotus lævicauda, Cryphæus laciniatus*. (*b*) Coblenz quartzite probably on the horizon of the Burnot conglomerate in the Eifel. (*a*) Greywacke with *Stropomena laticosta, Orthis circularis, Spirifer dunensis, Homalonotus ornatus, H. crassicauda*. Slates (Hundsrück, Taunus) with numerous trilobites (*Homalonotus ornatus, Phacops Ferdinandi, Cryphæus, Dalmanites, Orthoceras, Goniatites*, &c.) Taunus quartzite, Siegen grauwacke (*Spirifer primævus, S. hystericus, Rensseleria*, &c.) Sandstones, slates, phyllites, arkoses, ending downwards in conglomerates.

[140] See especially Gosselet's "Esquisse Geologique," and his great memoir on the Ardennes already cited.

[141] See the series of elaborate papers by E. Kayser in the Zeitschrift Deutsch. Geol. Gesell. vols. xxii. 1870, to xxxiii. 1881.

In the Harz, according to the researches of F. Roemer[142] and K. A. Lossen,[143] the Devonian system, which is there largely developed, consists of (1) a lower group of quartzites, graywackes, flinty slates, clay-slates, and associated bands of diabase (Taunus quartzite, Hundsrück shales, etc.), resting upon the graptolitic Wieda shales and Tanne graywacke; (2) a middle group composed of (*a*) Calceola-beds (Spirifer cultrijugatus, Calceola sandalina) and (*b*) Stringocephalus limestone (consisting of a lower crinoidal band and a massive limestone); and (3) an upper group consisting of (*a*) Cuboides-beds, limestones and marls, (*b*) Goniatite shales, (*c*) Cypridina shales. The eastern part of the region consists mainly of graywackes and slates which, with their associated igneous rocks attaining a great thickness in the Wieda slates, contain a number of simple graptolites and in the limestones underneath yield abundant trilobites belonging to genera familiar in the Upper Silurian rocks (Dalmanites, Cryphæus, Phacops, Bronteus, Acidaspis).

Representatives of the Devonian system reappear with local petrographical modifications, but with a remarkable persistence of general palæontological characters, in Eastern Thuringia, Franconia, Saxony, Silesia, the north of Moravia, and East Gallicia. Among the crumpled formations of the Styrian Alps, the evidence of organic remains has revealed the presence of Upper Devonian rocks with abundant Clymenias, Middle Devonian limestones with the characteristic Stringocephalus and numerous corals, and Lower limestones and slates with cephalopods and brachiopods.[144] Perhaps in other tracts of the Alps, as well as in the Carpathian range, similar shales, limestones, and dolomites, though as yet unfossiliferous, but containing ores of silver, lead, mercury, zinc, cobalt, and other metals, may be referable to the Devonian system.

To the west of central Europe the system has been recognized by its fossils in the Boulonnais, where its middle and upper members (Givetian, Frasnian, Famennian) are well exposed. In Normandy and Maine, sandstones (with Orthis Monnieri), are followed by limestones (with Homalonotus, Cryphæus, Phacops, etc.), and by upper graywackes

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[142] "Versteinerungen des Harzgebirges," 1843; "Rheinisch. Uebergangsgebirge," 1844.

[143] "Geologisch. Uebersichtskarte Harz," 1881.

[144] G. Stache, Zeitsch. Deutsch. Geol. Ges. 1884, p. 358; Frech, op. cit. 1887, p. 660, and authors there cited; 1891, p. 672.

and shales (with Pleurodictyum problematicum).[145] In Brittany also, Devonian strata are found, including representatives of the Famennian groups with Cypridinas and Goniatites, shales and limestones with Eifelian cephalopods, Pleurodictyum problematicum and Spirifer cultrijugatus, and a series of graywackes, sandstones, and shales with Chonetes sarcinulata, Phacops latifrons, etc.[146] In this region lies the limestone of Erbray (Loire Inférieure) so fully described by Barrois who, from its abundant corals, numerous brachiopods and gasteropods, and its trilobites of the genera Calymene, Phacops, Dalmanites, Proëtus, Harpes, Bronteus and Cheirurus, places it in the Gedinnian group at the base of the Lower Devonian series, and compares it with the Hercynian limestones of the Harz.[147] In the remarkable oasis of ancient rocks which has been already referred to as forming a conspicuous feature among the younger formations of Languedoc representatives of the three great divisions of the Devonian system have recently been worked out by F. Frech.[148] Again, the central Silurian zone of the Pyrenees is flanked on the north and south by bands of Devonian rocks (with broad-winged spirifers and other characteristic fossils), which have been greatly disturbed and altered. In the Asturias, according to Barrois, a mass of strata about 3280 feet thick contains representatives of the three divisions of the Devonian series, and has yielded an abundant fauna, numbering upward of 180 species, among which the corals and brachiopods are specially abundant.[149]

Throughout central Europe there occurs, in many parts of the Devonian areas, evidence of contemporaneous volcanic action in the form of intercalated beds of diabase, diabase-tuff, schalstein, etc. These rocks are conspicuous in the "greenstone" tract of the Harz, in Nassau, Saxony, Westphalia, and the Fichtelgebirge. Here and there, the tuff-bands are crowded with organic remains. It is also deserving of remark that over considerable areas (Ardennes, Harz, Sudeten-Gebirge, etc.) the Devonian sedimentary formations have assumed a more or less schistose character, and

[145] Oehlert, Bull. Soc. Geol. France, xvii. 1889, p. 742.
[146] Barrois, Ann. Soc. Geol. Nord, iv. xvi.
[147] "Faune du Calcaire d'Erbray," Mem. Soc. Geol. Nord, iii. 1889.
[148] Zeitsch. Deutsch. Geol. Ges. xxxix. 1887, p. 402.
[149] "Recherches sur les Terrains anciens des Asturies," etc., Mem. Soc. Geol. Nord. ii.

appear as quartzo-phyllades, quartzites, and other more or less crystalline rocks which were at one time supposed to belong to the "Archæan" series, but in which recognizable Devonian fossils have been found (ante, p. 1028). At numerous places, also, they have been invaded by masses of granite, quartz-porphyry, or other eruptive rocks, round which they present the characteristic phenomena of contact-metamorphism (pp. 1003–1005). These changes may have led to the subsequent development of the abundant mineral veins (Devon, Cornwall, Westphalia, etc.), whence large quantities of iron, tin, copper, and other metals have been obtained.

Russia.—In the northeast of Europe the Devonian and Old Red Sandstone types appear to be united, the limestones and marine organisms of the one being interstratified with the fish-bearing sandstones and shales of the others. In Russia, as was shown in the great work "Russia and the Ural Mountains," by Murchison, De Verneuil and Keyserling, rocks intermediate between the Upper Silurian and Carboniferous Limestone formations cover an extent of surface larger than the British Islands.[150] This wide development arises, not from the thickness, but from the undisturbed horizontal character of the strata. Like the Russian Silurian deposits, they remain to this day nearly as flat and unaltered as they were originally laid down. Judged by mere vertical depth, they present but a meagre representation of the massive Devonian graywacke and limestone of Germany, or of the Old Red Sandstone of Britain. Yet, vast as is the area over which they constitute the surface-rock, it probably forms only a small portion of their total extent; for they rise up from under the newer formations along the flank of the Ural chain. It would thus seem that they spread continuously across the whole breadth of Russia in Europe. Though almost everywhere undisturbed, they afford evidence of terrestrial oscillation immediately previous to their deposition, for they gradually overlap Upper and Lower Silurian rocks.

The chief interest of the Russian rocks of this age, as was

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[150] Besides the great work of these three pioneers the student will find much recent information regarding Russian geology in the Memoires du Comite Geologique of Russia. See for Devonian data T. Tschernyschew, vols. i. iii. (a detailed memoir on the lower, middle and upper divisions of the system in the Ural region).

first signalized by Murchison and his associates, lies in the union of the elsewhere distinct Devonian and Old Red Sandstone types. In some districts, these rocks consist largely of limestones, in others of red sandstones and marls. In the former, they present mollusks and other marine organisms of known Devonian species; in the latter, they afford remains of fishes, some of which are specifically identical with those of the Old Red Sandstone of Scotland. The distribution of these two palæontological facies in Russia is traced by Murchison to the lithological characters of the rocks, and consequent original diversities of physical conditions, rather than to differences of age. Indeed, cases occur where, in the same band of rock, Devonian shells and Old Red Sandstone fishes lie commingled. In the belt of the formation which extends southward from Archangel and the White Sea, the strata consist of sands and marls, and contain only fish remains. Traced through the Baltic provinces, they are found to pass into red and green marls, clays, thin limestones, and sandstones, with beds of gypsum. In some of the calcareous bands such fossils occur as Orthis striatula, Spiriferina prisca, Leptæna productoides, Spirifer Anossofi, S. Archiaci, S. Verneuili, Rhynchonella cuboides, Spirorbis omphaloides, and Orthoceras subfusiforme. The lower parts of the series contain Osteolepis, Dipterus, Diplopterus, and Asterolepis (Homosteus), while in the higher beds Holoptychius, Glyptosteus, and other well-known fishes of the Upper Old Red Sandstone occur. Followed still further to the south, as far as the watershed between Orel and Woronesch, the Devonian rocks lose their red color and sandy character, and become thin-bedded yellow limestones, and dolomites with soft green and blue marls. Traces of salt deposits are indicated by occasional saline springs. It is evident that the geographical conditions of this Russian area during the Devonian period must have resembled those of the Rhine basin and central England during the Triassic period. There is an unquestionable passage of the uppermost Devonian rocks of Russia into the base of the Carboniferous system, but a complete break between them and the highest Silurian strata. The lowest parts of the British Old Red Sandstone, containing Pterygotus, Cephalaspis, Pteraspis, etc., are wanting. Devonian rocks have been recognized in other parts of the vast Russian empire, across Siberia in the Altai mountains, in Asia Minor, and in Africa.

North America.—The Devonian system, as developed in the Northern States, and eastern Canada and Nova Scotia, pre-

sents much geological interest in the union which it contains of the same two distinct petrographical and biological types found in Europe. Traced along the Allegheny chain, through Pennsylvania, into New York, the Devonian rocks are found to contain a characteristic suite of marine organisms comparable with those of the Devonian system of Europe. But on the eastern side of the great range of Silurian hills in the northeastern States, we encounter in New Brunswick and Nova Scotia a succession of red and yellow sandstones, limestones, and shales nearly devoid of marine organisms, yet full of land-plants, and with occasional traces of fish remains. The marine type is well developed above the Silurian series in Nevada.

The marine or Devonian type has been grouped in the following subdivisions by the geologists of New York:

UPPER DEVONIAN.	Catskill Red Sandstone, with fish remains (Holoptychius). Chemung group: Spirifer Verneuili. Portage group: Goniatites, Cardiola, Clymenia. Genesee group: Rhynchonella cf. cuboides.
MIDDLE DEVONIAN.	Hamilton group: Phacops, Homalonotus, Cryphæus. Marcellus group: Goniatites.
LOWER DEVONIAN.	Corniferous limestone: Spirifer acuminatus, S. gregarius, Dalmanites, Proëtus. Onondaga limestone, Schoharie grit, Cauda-galli grit. This and the Corniferous limestone are bracketed together as the Upper Helderberg group. Oriskany sandstone: Spirifer arenosus, Rensseleria ovoides. Lower Helderberg group consisting of *c.* Upper Pentamerus limestone: Pentamerus pseudo-galeatus. *b.* Delthyris limestone: Meristella lævis. *a.* Lower Pentamerus limestone: Pentamerus galeatus.

In the Lower Devonian series, traces of terrestrial plants (Psilophyton, Caulopteris, etc.) have been detected, even as far west as Ohio. Corals (cyathophylloid forms, with Favosites, Syringopora, etc.) abound especially in the Corniferous Limestone, perhaps the most remarkable mass of coral-rock in the American Palæozoic series, and from which Hall has made a magnificent collection of specimens. Among the brachiopods are species of Pentamerus, Stricklandinia, Rhynchonella, and others, with the characteristic European form Spirifer cultrijugatus, and the world-wide Atrypa reticularis. The trilobites include the genera Dalmanites, Proetus, and Phacops. Remains of fishes occur in the Corniferous group, consisting of ichthyodorulites and teeth of cestraciont and hybodont placoids, with plates, bones, and

teeth of some peculiar ganoids (Macropetalichthys, Onychodus).

In the Marcellus shale, Hamilton beds, and Genesee shale remains of land-plants occur, but much less abundantly than among the rocks of New Brunswick. Brachiopods are especially abundant among the sandy beds in the centre of the formation. They comprise, as in Europe, many broad-winged spirifers (S. mucronatus, etc.), with species of Productus, Chonetes, Athyris, etc. The earliest American Goniatites have been noticed in these beds. Newberry has described a gigantic fish (Dinichthys) from the Black Shale of Ohio.

The Portage and Chemung groups have yielded land-plants and fucoids, also some crinoids, numerous broad-winged spirifers, with Aviculæ and a few other lamellibranchs. These strata, in the New York region, consist of shales and laminated sandstones, which there attain a maximum thickness of upward of 2000 feet, but die out entirely toward the interior. They are covered by a mass of red sandstones and conglomerates—the Catskill group, which is 2000 or 3000 feet thick in the Catskill Mountains, and thickens along the Appalachian region to 5000 or 6000 feet. These red arenaceous rocks bear a striking similarity in their lithological and biological characters to the Old Red Sandstone of Europe. As a whole they are unfossiliferous, but they have yielded some ferns like those of the Upper Old Red Sandstone of Ireland and Scotland (Archæopteris), some characteristic genera of fish, as Holoptychius and Bothriolepis, and a large lamellibranch closely resembling the Irish Anodonta. The Old Red Sandstone development, found on the eastern side of the crystalline ridge which runs southward from Canada far into the States, is described at p. 1332.

Asia.—From southwestern China, Richthofen brought a series of marine fossils which show the presence there of strata probably referable to Middle and Upper Devonian horizons. Out of 28 species named by Kayser, no fewer than 13 are cosmopolitan, including such familiar forms as Rhynchonella cuboides, R. pugnus, Pentamerus galeatus, Atrypa reticularis (var. desquamata), Merista plebeia, Spirifer Verneuili, Orthis striatula, Productus subaculeatus, Strophalosia productoides, Aulopora tubæformis.[151]

[151] Richthofen, "China," vol. iv. p. 75.

Australasia.—In New South Wales, the presence of Devonian rocks was determined by W. B. Clarke from the evidence of fossil remains. The thickness of strata (sandstones, quartzites, conglomerates, shales and limestones) is in some places estimated at not less than 10,000 feet, passing down into Silurian and upward into Carboniferous strata. Among the numerous fossils are many forms familiar in corresponding strata in Europe and America, such as Cyathophyllum damnoniense, Favosites reticulata, F. fibrosa, F. Goldfussi, Heliolites porosa, Chonetes laguessiana (hardrensis), Orthis striatula, Rhynchonella pleurodon, R. pugnus, Atrypa reticularis, Spirifer Verneuili.[152] In Victoria certain limestones found at Bindi on the Tambo river and elsewhere have yielded characteristically Middle Devonian fossils, including Favosites Goldfussi, Spirifer lævicostatus, Chonetes australis, and a placoderm fish. With these rocks are associated contemporaneous felsitic lavas and tuffs. Other strata are referred to the Upper Devonian series.[153]

Devonian rocks play an important part in the structure of New Zealand. To the lower part of the system are assigned quartzites, cherts, and limestones, which in the South Island at Reefton have yielded Spirifer vespertilio and Homalonotus expansus. To the Upper Devonian series should probably be referred the enormously thick Te Anau group of "greenstone-breccias, aphanite-slates, diorite-sandstones, with great contemporaneous flows and dikes of diorite, serpentine, syenite, and felsite." These rocks form important mountain ranges in the South Island, and at Reefton are the matrix of the auriferous reefs. They rest unconformably on the Lower Devonian and pass up into the Maitai series (Carboniferous).[154]

II. OLD RED SANDSTONE TYPE

§ 1. General Characters

Under the name of Old Red Sandstone, is comprised a vast and still imperfectly described series of red sandstones, shales, and conglomerates, intermediate in age be-

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[152] See the authors cited on p. 1290, note.

[153] R. A. F. Murray, "Victoria—Geology and Physical Geology," 1887.

[154] Hector, "Handbook of New Zealand," p. 36.

tween the Ludlow rocks of the Upper Silurian and the base of the Carboniferous system in Britain. These rocks were termed "Old" to distinguish them from a somewhat similar series overlying the Coal-measures, to which the name "New" Red Sandstone was applied. When the term Devonian was adopted it speedily supplanted that of Old Red Sandstone, inasmuch as it was founded on a type of marine strata of wide geographical extent, whereas the latter term described what appeared to be merely a British and local development. For the reasons already given, however, it is desirable to retain the title Old Red Sandstone as descriptive of a remarkable suite of deposits to which there is little or nothing analogous in typical Devonian rocks. The Old Red Sandstone of Europe is almost entirely confined to the British Isles. It was deposited in separate areas or basins, the sites of some of which can still be traced. Their diversities of sediment and discrepancy of organic contents point to the absence, or at least rare existence, of any direct communication between them. It was maintained many years ago by Fleming and still more explicitly by Godwin-Austen, and was afterward enforced by A. C. Ramsay, that these basins were lakes or inland seas. The character of the strata, the absence of unequivocally marine fossils, the presence of land-plants and of numerous ganoid fishes, which have their modern representatives in rivers and lakes, suggest and support this opinion, which has been generally adopted by geologists.[155] The red arenaceous and marly strata which, with their fish-remains and land-plants, occupy a depth of many thousand feet be-

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[155] For a history of opinion on this subject see Trans. Royal Soc. Edin. xxviii. 1869, p. 346.

tween the top of the Silurian and the base of the Carboniferous systems, are regarded as the deposits of a series of lakes or inland seas formed by the uprise of portions of the Silurian sea-floor. The length of time during which these lacustrine basins must have existed is shown, not only by the thickness of the deposits formed in them, but by the complete change which took place in the marine fauna between the Silurian and Carboniferous periods. The prolific fauna of the Wenlock and Ludlow rocks was driven away from Western Europe by the geographical revolutions which, among other changes, produced the lake-basins of the Old Red Sandstone. When a marine population—crinoids, corals, and shells—once more overspread that area, it was a completely different one. So thorough a change must have demanded a long interval of time.

ROCKS.—As shown by the name of the type, red sandstone is the predominant rock. The color varies from a light brick-red to a deep chocolate-brown, and occasionally passes into green, yellow, or mottled tints. The sandstones are for the most part granular siliceous rocks, wherein the component grains of clear quartz are coated and held together by a crust of earthy ferric oxide. In no part of the geological record is the prevalence of this red material more marked than in the Old Red Sandstone. The conditions that led to the precipitation of this oxide in such quantity are not yet well understood.[156] Scattered pebbles of quartz or of various crystalline rocks are frequently noticeable among the sandstones, and this character affords a passage into con-

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[156] See postea, p. 1322. Mr. I. C. Russell in a memoir already cited, on the subaerial decay of rocks and the origin of the red color of certain formations, concludes that in the majority of cases the ferric oxide was deposited during the subaerial decay of the rocks from which the sediment was derived. Bull. U. S. Geol. Surv. No. 52, 1889.

glomerate. The latter rock forms a conspicuous feature in many Old Red Sandstone districts. It varies in thickness from a mere thin bed up to successive massive beds, having a united thickness of several thousand feet. The pebbles vary much in composition and size. They consist of quartz, quartzite, graywacke, granite, syenite, quartz-porphyry, gneiss, felsite, or any durable material, and their varying nature serves to distinguish some bands of conglomerate from others. They are of all sizes up to blocks eight feet or more in length. They are sometimes tolerably angular, particularly where the conglomerate rests upon schists or other rocks which weather into angular blocks. In the upper Old Red Sandstone, thick accumulations of subangular conglomerate or breccia recall some glacial deposits of modern times. For the most part the stones in the conglomerates are well rounded, sometimes indeed remarkably so, even when they are a foot or more in diameter. The larger blocks are usually angular fragments that have been derived from rocks in the immediate neighborhood. The smaller rounded stones have often come from some distance; at least it is impossible to discover any near source for them. Bands of red and green clay or marl occur, in which seams and nodules of cornstone may not infrequently be observed. Here and there, too, the sandstones assume a flaggy character, and sometimes pass into fine gray or olive-colored shales and flagstones. Organic remains occur in some of these gray beds, but are usually absent from the red strata, though in some of the conglomerates teeth, scales, and broken bones of fishes are not uncommon. In the north of Scotland, peculiar very hard calcareous and bituminous flagstones are largely developed, and have yielded the chief part of the remarkable ichthyic fauna of the system. In Scotland, also,

contemporaneously erupted diabases, porphyrites, felsites, and tuffs play an important part in the petrography of the Old Red Sandstone, seeing that they attain a thickness in some places of more than 6000 feet, and form important ranges of hills. They point to the existence of extensive volcanic eruptions from numerous vents in the lakes or inland basins in which the sediments were accumulated.

LIFE.—No greater contrast is to be found between the organic contents of any two successive groups of rock than that which is presented by a comparison of the Upper Silurian and Old Red Sandstone systems of Western Europe. The abundant marine fauna of the Ludlow period disappeared from the region. As soon as the red rocks begin, the fossils rapidly die out. Some traces of the aquatic plants that grew in the fresh-water lakes have been detected. An abundant fossil, originally referred to the vegetable kingdom and named Parka by Fleming, was afterward considered to be more probably the egg-packets of the large crustaceans which abounded in these waters. More recently, however, this organism has been carefully studied by Sir J. W. Dawson and Prof. D. P. Penhallow, who have come to the conclusion that it represents what were aquatic plants with creeping stems, linear leaves and sessile sporocarps bearing two kinds of sporangia.[157] On the land that surrounded the lakes or inland seas of the period, there grew the oldest terrestrial vegetation of which more than mere fragments are known. It has been scantily preserved in the ancient lake-bottoms in Europe; more abundantly in Gaspé and New Brunswick. The American localities have yielded to the long-continued researches of Sir J. W. Dawson more than

[157] Trans. Roy. Soc. Canada, ix. 1891, sect. iv. pp. 3–16.

100 species of land-plants. They are almost all acrogens, lycopods and ferns being largely predominant. Among the distinctive forms the following may be mentioned: Psilophyton (Fig. 350), Arthrostigma, Leptophleum, and Prototaxites. Forty-nine ferns include the genera Palæopteris (Cyclopteris), Neuropteris, Sphenopteris, and some tree-ferns

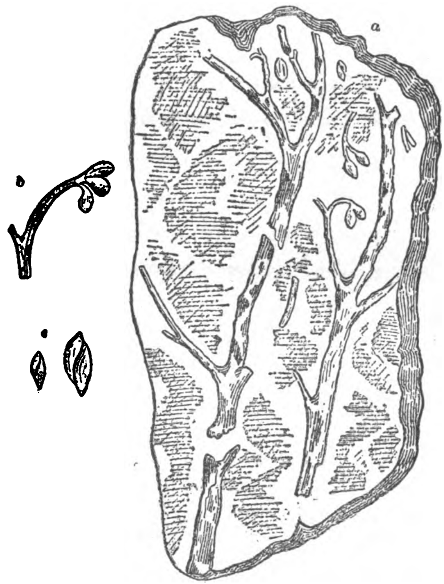

Fig. 350.—Psilophyton robustum, Dawson. Lower Old Red Sandstone, Perthshire. Drawn by Mr. R. Kidston.
a, specimen of the plant ½ nat. size; *b*, fructification; *c*, empty spore-cases.

(Psaronius, Caulopteris). Lepidodendroid and sigillaroid plants abound, as well as calamites. Higher forms of vegetation are represented by a few conifers (Dadoxylon, Ormoxylon,[158] etc.). From a locality on Lake Erie, Dawson describes a fragment of what he believes to be dicotyledo-

[158] Mem. Geol. Survey Canada, 1871; op. cit. 1873. Q. J. Geol. Soc. 1881, p. 299. "Acadian Geology," 2d edition. Prototaxites, included by Dawson among the Coniferæ, is relegated by Mr. Carruthers to the Algæ under the name of Nematophycus—a genus also found in the Upper Silurian rocks of N. Wales. Month. Microscopical Journ. 1872.

nous wood, not unlike that of some modern trees—the most ancient fragment of an angiospermous exogen yet discovered. So abundant are the vegetable remains that in some layers they actually form thin seams of coal.

The interest of this flora is heightened by the discovery of the fact that the primeval forests were not without the hum of insect life. The most ancient known relics of insect forms have been recovered from the Devonian strata of New Brunswick.[159] They include both orthopterous and neuropterous wings, and have been regarded by Mr. Scudder of Boston as combining a remarkable union of characters now found in distinct orders of insects. In one fragment he observed a structure which he could only compare to the stridulating organ of some male Orthoptera. Another wing indicates the existence of a gigantic Ephemera, with a spread of wing extending to five inches. The continued existence of scorpions during this period has been established by the discovery of two genera (Palæophoneus and Proscorpius) in the Lower Helderberg rocks of New York.

The existence of myriapods in the forests of this ancient period has been shown by Mr. B. N. Peach, who finds that the so-called Kampecaris, previously regarded as a larval form of isopod crustacean, really contains two genera of chilognathous myriapods differing from other known forms, fossil and recent, in their less differentiated structure, each body segment being separate, and supplied with only one pair of walking legs.[160] There were also pulmoniferous shells, of which one species (Strophites grandæva, Dawson) occurs in the plant-beds of St. John, New Brunswick.

[159] For a synopsis of all known species of fossil insects up to the year 1890, see Bull. U. S. Geol. Surv. No. 71, 1891.

[160] Proc. Phys. Soc. Edin. vii. 1882, p. 179.

The water-basins of the Old Red Sandstone might be supposed to have been, on the whole, singularly devoid of life; for remains of it have been but meagrely preserved. Never-

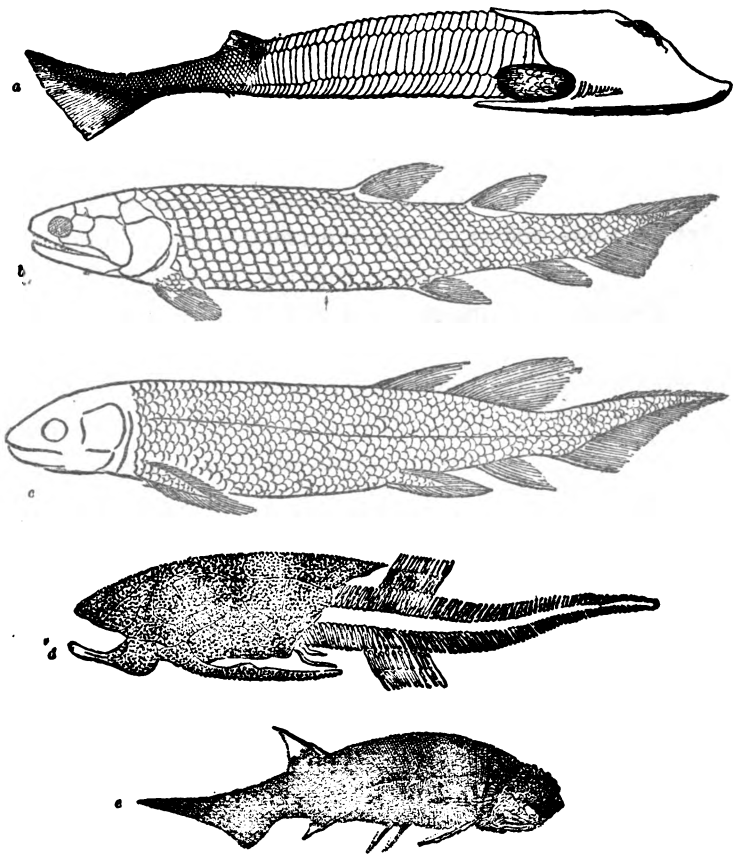

Fig. 351.—Lower Old Red Sandstone Fishes.

a, Cephalaspis Lyelli, Ag. (side view), restored by Professor Ray Lankester; *b*, Osteolepis microlepidotus, Sedgw. and Murch., restored by Dr. Traquair; *c*, Dipterus Valenciennesii, Sedgw. and Murch., from a sketch by Dr. Traquair; *d*, Coccosteus decipiens, Ag; *e*, Mesacanthus (Acanthodes) Mitchelli, Eg., Forfarshire, from a sketch by Mr. B. N. Peach.

theless, in some basins at least (Caithness, Moray Firth), it must have been exceedingly abundant, as is shown by the extraordinary profusion of the fossils. The fauna consists

almost wholly of fishes (Figs. 351, 352). Among these the Pteraspis survived for a while from Upper Silurian times. With it there lived other forms (Scaphaspis, Holaspis) and genera of the allied family of the Cephalaspidæ. The ancient order of Dipnoi, which still survives in a few forms in some African and Australian rivers (Protopterus, Ceratodus), was represented in the lakes of the Lower Old Red Sandstone by the abundant Dipterus, and in those of the Upper by Phaneropleuron. But the ganoids were the most varied order in these waters, being represented by a number of families. Besides those which lingered on from the Upper Silurian period there now appeared the striking group of the Asterolepids of which Asterolepis and Pterichthys (Fig. 352), are characteristic genera. Bothriolepis appears to be confined to the Upper Old Red Sandstone, where it sometimes occurs with other genera crowded together on the surfaces of the layers of stone, as if the fishes had been killed suddenly and had been covered over with sediment where they died. The family of the Coccosteids includes the type genus Coccosteus and the gigantic Homosteus (Asterolepis). This latter form appears to have been the largest fish of the period in the European area, its massive cuirass-like head-shield sometimes measuring twenty inches in length by sixteen in breadth. The sub-order of Acanthodians, marked by their strong fin-spines, attained a great development in the waters of this period; among their genera are Mesacanthus (Acanthodes), Cheiracanthus, Ischnacanthus (Diplacanthus), Rha-

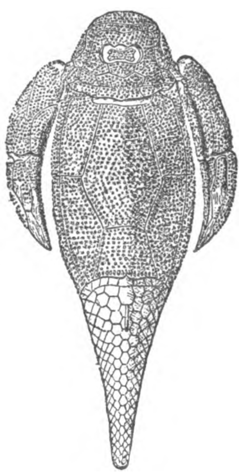

Fig. 352.
Pterichthys cornutus, Ag.

dinacanthus. The sub-order Crossopterygidæ, so remarkable for the central scaly lobe of their fins, and represented at the present time by Polypterus, swarmed in the waters, some of the most characteristic genera being Tristichopterus, Gyroptichius, Glyptolepis, Osteolepis, Thursius, and Diplopterus which are found in the Lower Old Red Sandstone of Scotland, and Holoptychius which is a characteristic fish of the Upper division of the system. Of the sturgeon tribe there were some small representatives belonging to the genus Cheirolepis.[161] The Dinichthys, already referred to as occurring in the Devonian rocks of North America, was probably one of the largest and most formidable of these early fishes. Its head alone incased in strong plates attained a length of 3 feet, and was armed with a powerful apparatus of teeth.

A few eurypterids occur, especially of the genera Eurypterus and Pterygotus (Fig. 348). The species of the former are small, but one of the latter, P. anglicus, is found in Scotland, which must have had a length of five or six feet.

§ 2. Local Development

Britain.—Murchison, who strongly advocated the opinion that the Old Red Sandstone and Devonian rocks represent different geographical conditions of the same period, and who had with satisfaction seen the adoption of the Devonian classification by Continental geologists, endeavored to trace in the Old Red Sandstone of Britain a threefold division, like that which had been accepted for the Devonian system. He accordingly arranged the formations as in the subjoined table:

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[161] Traquair, Geol. Mag. 1888, p. 507. M. Lohest, Ann. Soc. Geol. Belg. xv. 1888, p. 112. Whiteaves, Canad. Nat. x. Nos. 1, 2, 1881.

Old Red Sandstone as classified by Murchison.	Upper.	Yellow and red sandstones and conglomerates: Pterichthys major, Holoptychius nobilissimus, etc. = Dura Den beds.
	Middle.	Gray and blue calcareous and bituminous flagstones, limestones, and red sandstones and conglomerates: Dipterus, Osteolepis, Asterolepis, Acanthodes, Pterichthys, etc. = Caithness flags.
	Lower.	Red and purple sandstones, gray sandy flagstones, and coarse conglomerates: Cephalaspis, Pteraspis, Pterygotus = Arbroath flags.

It is important to observe that in no district can these three subdivisions be found together, and that the so-called "middle" formation occurs only in one region—the north of Scotland. The classification, therefore, does not rest upon any actually ascertained stratigraphical sequence, but on an inference from the organic remains. The value of this inference will be estimated a little further on. All that can be affirmed from the stratigraphical evidence of any district in Britain is that a great physical and palæontological break can generally be traced in the Old Red Sandstone, dividing it into two completely distinct series.[162]

As a whole, the Old Red Sandstone, where its strata are really red, is, like other masses of red deposits, singularly barren of organic remains. As above remarked, the physical conditions under which the precipitation of iron oxide took place are not easily explained. They were evidently unfavorable for the development of animal life in the same waters. Sir A. C. Ramsay has connected the occurrence of such red formations with the existence of salt lakes, from the bitter waters of which not only iron oxide but often rock-salt, magnesian limestone, and gypsum were thrown down.[163] He points also to the presence of land-plants, footprints of amphibia, and other indications of terrestrial surfaces, while truly marine organisms are either found in a stunted condition or are absent altogether. Where the strata of the Old Red Sandstone, losing their red color and ferruginous character, assume gray or yellow tints and pass into a calcareous or argillaceous condition, they not infrequently become fossiliferous. At the same time, it is worthy of remark that

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162 Q. J. Geol. Soc. xviii. 1860, p. 312.

163 Prof. Gosselet contends that the precipitation of iron might quite well have taken place in the sea, and he cites the case of the Devonian basin of Dinant, where the same beds are in one part red and barren of organic remains, and in another part of the same area are of the usual colors and are full of marine fossils. But the red color of the Old Red Sandstone is general, and is accompanied with other proofs of isolation in the basins of deposit (see p. 1314).

the red conglomerates, which might be supposed little likely to contain organic remains, are occasionally found to be full of detached scales, plates, and bones of fishes.

The Old Red Sandstone of Britain, according to the author's researches, consists of two subdivisions, the lower of which passes down conformably into the Upper Silurian deposits, the upper shading off in the same manner into the base of the Carboniferous system, while they are separated from each other by an unconformability.

1. LOWER.—Red sandstones, conglomerates, flagstones, and associated igneous rocks, passing in some places conformably down into Upper Silurian formations, elsewhere resting unconformably on Dalradian or other older rocks—Dipterus, Coccosteus, Cephalaspis, Pterygotus, etc.

In a memoir on the Old Red Sandstone of Western Europe, the author has proposed short names for the different detached basins in which the Lower Old Red Sandstone was accumulated.[164] The most southerly of these (the Welsh Lake) lies in the Silurian region extending from Shropshire into South Wales. Here the uppermost parts of the Silurian system graduate into red strata, not less than 10,000 feet thick, which in turn pass up conformably into the base of the Carboniferous system. This vast accumulation of red rocks consists in its lower portions of red and green shales and flagstones, with some white sandstones and thin cornstones; in the central and chief division, of red and green spotted sandy marls and clays, with red sandstones and cornstones; in the higher parts, of gray, red, chocolate-colored, and yellow sandstones, with bands of conglomerate. No unconformability has yet been proved in any part of this series of rocks, though, from the observations of De la Beche and Jukes, it may be suspected that the higher strata, which graduate upward into the Carboniferous formations, are separated from the underlying portions of the Old Red Sandstone by a distinct discordance.[165]

Although, as a whole, barren of organic remains, these red rocks have here and there, more particularly in the calcareous zones, yielded fragments of fishes and crustaceans. In their lower and central portions remains of the fishes Cephalaspis, Didymaspis, Scaphaspis, Pteraspis, and Cya-

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164 Trans. Roy. Soc. Edin. xxviii. 1879.

165 De la Beche, Mem. Geol. Surv. vol. i. 1846, p. 50. J. B. Jukes, Letters, etc. 1871, p. 508; letter to A. C. Ramsay, dated 1857. Symonds, "Records of the Rocks," 1872; Hughes, Brit. Assoc. Rep. 1875, sects. p. 70.

thaspis, have been found, together with crustaceans of the genera Stylonurus, Pterygotus, Prearcturus, and obscure traces of plants. The upper yellow and red sandstones contain none of the cephalaspid fishes, which are there replaced by Pterichthys and Holoptychius, associated with distinct impressions of land-plants. In some of the higher parts of the Old Red Sandstone of South Wales and Shropshire, Serpula and Conularia occur, but these are exceptional cases, and point to the advent of the Carboniferous marine fauna, which doubtless existed outside the British area before it spread over the site of the Old Red Sandstone basins (see p. 1329).

It is in Scotland[166] that the Old Red Sandstone shows the most complete and varied development, alike in physical structure and in organic contents. Throughout that country the system is found to consist of two well-marked groups of strata, separated from each other by a strong unconformability and a complete break in the succession of organic remains. Each subdivision occurs in distinct basins of deposit. The most important basin of the Lower Old Red Sandstone occupies the central valley, between the base of the Highland mountains and the Uplands of the southern counties (Lake Caledonia). On the northeast, it presents a series of noble cliff-sections along the coast-line from Stonehaven to the mouth of the Tay. On the southwest it ranges by the island of Arran and the south of Cantyre across St. George's Channel into Ireland, where it runs almost to the western seaboard, flanked on the north, as in Scotland, by hills of crystalline rocks, and on the south chiefly by a Silurian belt. In this basin abundant volcanic action manifested itself across the whole breadth of Scotland and in the north of Ireland. Another distinct and still larger basin (Lake Orcadie) of the lower subdivision lies on the north side of the Highlands, but only a portion of it emerges above the sea in the north of Scotland. Skirting the slopes of the mountains along the Moray Firth and the east of Ross and Sutherland, it stretches through Caithness and the Orkney Islands as far as the south of the Shetland group, and may possibly have been at one time continued as far as the Sognefjord and Dalsfjord in Norway, where red conglomerates

166 See Agassiz, "Poissons du Vieux Grès Rouge," Hugh Miller's "Old Red Sandstone" and "Footprints of the Creator"; J. Anderson's "Dura Den"; Explanations Geol. Surv. Scotland, sheets 14, 15, 23, 24, 32, 33, 34; author's memoir cited on previous page, and papers referred to in subsequent notes.

like those of the north of Scotland occur. There is even reason to infer that it may have ranged eastward into Russia, for, as already stated, some of its most characteristic organisms are found also among the Devonian strata of that country. Several distinct contemporaneous volcanic centres have been detected in this basin. A third minor area of the Lower Old Red Sandstone (Lake Cheviot) lay on the south side of the Southern Uplands, over the east of Berwickshire and the north of Northumberland, including the area of the Cheviot Hills, where a copious volcanic series has been preserved. A fourth (Lake of Lorne) occupied a basin on the flanks of the southwest Highlands, which is now partly marked by the terraced volcanic hills of Lorne. There is sufficient diversity of lithological and palæontological characters to show that these several areas were on the whole distinct basins, separated both from each other and from the sea. The interval between the Lower and Upper Old Red Sandstone was so protracted, and the geographical changes accomplished during it were so extensive, that the basins in which the late parts of the system were deposited only partially correspond with those of the older lakes.

In the central basin, or Lake Caledonia, both divisions of the Old Red Sandstone are typically seen. The lower series of deposits, attaining a maximum depth of perhaps 20,000 feet, everywhere presents traces of shallow-water conditions. The accumulation of so great a thickness of sediment can only be explained on the supposition that the subterranean movements, which at first ridged up the Silurian sea-floor into land, inclosing separate basins, continued to deepen these basins, until, eventually, enormous masses of sediment had slowly gathered in them. This massive series of deposits passes down conformably in Lanarkshire into Upper Silurian rocks; elsewhere its base is concealed by later formations, or by the unconformability with which different horizons rest upon the older rocks. Covered unconformably by every rock younger than itself, it consists of reddish-brown or chocolate-colored, gray, and yellow sandstones, red shales, gray flagstones, coarse conglomerates, with occasional bands of limestone and cornstone. The gray flagstones and thin gray and olive shales and "calmstones" are almost confined to Forfarshire, in the northeast part of the basin, and are known as the "Arbroath flags." One of the most marked lithological features in this central Scottish basin is the occurrence in it of extensive masses of interbedded volcanic rocks.

These, consisting of diabases, porphyrites, felsites, and tuffs, attain a thickness of more than 6000 feet, and form important chains of hills, as in the Pentland, Ochil, and Sidlaw ranges. They lie several thousand feet above the base of the system, and are regularly interstratified with bands of the ordinary sedimentary strata. They point to the outburst of numerous volcanic vents along the lake or inland sea in which the Lower Old Red Sandstone of central Scotland was laid down; and their disposition shows that the vents ranged themselves in lines or linear groups, parallel with the general trend of the great central valley. The fact that the igneous rocks are succeeded by thousands of feet of sandstones, shales, and conglomerates, without any intercalation of lava or tuff, proves that the volcanic episode in the history of the lake came to a close long before the lake itself disappeared.[167] As a rule, the deposits of this basin are singularly unfossiliferous, though some portions of them, particularly in the Forfarshire (Arbroath) flagstone group, have proved rich in remains of crustaceans and fish. Nine or more species of crustaceans have been obtained, chiefly eurypterids, but including one or two phyllopods. The large pterygotus (P. anglicus) is especially characteristic, and must have attained a great size, for some of the individuals indicate a length of 6 feet, with a breadth of 1½ feet. There occur also a smaller species (P. minor), two Eurypteri, and three species of Stylonurus. Upward of twenty species of fishes have been obtained, chiefly from the Arbroath flags, belonging to the sub-orders Acanthodidæ and Ostracostei (Fig. 351). One of the most abundant forms is the little Mesacanthus (Acanthodes) Mitchelli. Another common fish is Ischnacanthus (Diplacanthus) gracilis. There occur also Climatius scutiger, C. reticulatus, C. uncinatus, C. Macnicoli, C. grandis, C. gracilis, Parexus incurvus, Cephalaspis Lyellii, and Pteraspis Mitchelli. Some of the sandstones and shales are crowded with indistinctly preserved vegetation, occasionally in sufficient quantity to form thin laminæ of coal. The egg-like impressions known as Parka decipiens and referred to on p. 1316 also abound in some layers. In Forfarshire, the surfaces of the shaly flagstones are now and then covered with linear grass-like plants, like the sedgy vegetation of a lake or marsh. In Perthshire, certain layers occur, chiefly made up of com-

[167] Presidential Address, Quart. Journ. Geol. Soc. 1882, p. 62 *et seq.*

pressed stems of Psilophyton (Fig. 350). The adjoining land was doubtless clothed with a flora in large measure lycopodiaceous.

The Old Red Sandstone of the northern basin (Lake Orcadie) is typically developed in Caithness, where it consists chiefly of the well-known dark-gray bituminous and calcareous flagstones of commerce. It rests unconformably upon various crystalline schists, granites, etc., and must have been deposited on the very uneven bottom of a sinking basin, seeing that occasionally even some of the higher platforms are found resting against the more ancient rocks. The lower zones consist of red sandstones and conglomerates, which graduate upward into the flagstones. Other red sandstones, however, supervene in the higher parts of the system. The total depth of the series in Caithness has been estimated at upward of 16,000 feet. Murchison was the first to attempt the correlation of the Caithness flagstones with the Old Red Sandstone of the rest of Britain. Founding upon the absence from these northern rocks of the cephalaspidean fishes characteristic of the admitted Lower Old Red Sandstone in the south of Scotland and in Wales and Shropshire, upon the presence of numerous genera of fishes not known to occur elsewhere in the true Lower Old Red Sandstone, and upon the discovery of a Pterygotus in the basement red sandy group of strata, he concluded that the massive flagstone series of Caithness could not be classed with the Lower Old Red Sandstone, but must be of younger date. He supposed the red sandstones, conglomerates, and shales at the base, with their Pterygotus, to represent the true Lower Old Red Sandstone, while the great flagstone series with its distinctive fishes was made into a middle division answering in some of its ichthyolitic contents to the Middle Devonian rocks of the Continent. This view was accepted by geologists. I have, however, endeavored to show that the Caithness flagstones belong to the Lower Old Red Sandstone, and that there is no evidence of the existence of any middle division. It appears to me that the discrepancy in organic contents between the Caithness and the Arbroath flags is by no means so strong as Murchison supposed, but that several species are common to both. In particular, I find that the characteristically Lower Old Red Sandstone and Upper Silurian crustacean genus Pterygotus occurs, not merely in the basement zone of the Caithness flags, but also high up in the series. The genera Acanthodes (Mesacanthus) and Diplacanthus (Isch-

nacanthus) appear both in Caithness and in Forfarshire. Parexus incurvus occurs in the northern as well as the southern basin. The admitted palæontological distinctions are probably not greater than the striking lithological differences between the strata of the two regions would account for, or than the contrast between the ichthyic faunas of adjacent but disconnected water-basins at the present time.

More than sixty species of fishes have been obtained from the Old Red Sandstone of the north of Scotland. Among these, the genera Acanthodes, Asterolepis, Cheiracanthus, Cheirolepis, Coccosteus, Diplacanthus, Diplopterus, Dipterus, Glyptolepis, Osteolepis, and Pterichthys are specially characteristic. Some of the shales are crowded with the little phyllopod crustacean Estheria membranacea. Land-plants abound, especially in the higher groups of the flagstones, where forms of Psilophyton, Lepidodendron, Stigmaria, Sigillaria, Calamites, and Cyclopteris, as well as other genera, occur. In the Shetland Islands, traces of abundant contemporaneous volcanic rocks have been observed.[168] These, with the exception of two trifling examples in the region of the Moray Firth, are the only known instances of volcanic action in the Lower Old Red Sandstone of Lake Orcadie. In the other two Scottish basins, those of the Cheviot Hills[169] and of Lorne,[170] volcanic action long continued vigorous, and produced thick piles of lava, like those of Lake Caledonia.

2. UPPER.—This division consists of yellow and red sandstones, conglomerates, marls, etc., passing up conformably into the base of the Carboniferous system, and resting unconformably on the Lower Old Red Sandstone and every older formation. Among its distinctive fossils are Holoptychius, Bothriolepis (Pterichthys) major, etc.

Below the Carboniferous system there occur in Scotland certain red sandstones, deep-red clays or marls, conglomerates, and breccias, the sandstones passing into yellow or even white. These strata, wherever their stratigraphical relations can be distinctly traced, lie unconformably upon every formation older than themselves, including the Lower

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[168] Trans. Roy. Soc. Edin. xxviii. 1878, p. 345. Presidential Address, Quart. Journ. Geol. Soc. xlviii. 1892, p. 94. Peach and Horne, Trans. Roy. Soc. Edin. xxxii. 1884, p. 359.

[169] C. T. Clough, "Cheviot Hills," Geol. Surv. Mem. Sheet 108 N.E., 1888; J. J. H. Teall, Geol. Mag. 1883.

[170] Presidential Address, Quart. Journ. Geol. Soc. xlviii. 1892, p. 95.

Old Red Sandstone, while, on the other hand, they pass up conformably into the Carboniferous rocks above. As already remarked, they were deposited in basins, which only partially corresponded with those wherein the Lower Old Red Sandstone had been laid down. Studied from the side of the underlying formations, they seem naturally to form part of the Old Red Sandstone, since they agree with it in general lithological character, and also in containing some distinctively Old Red Sandstone genera of fishes, such as Pterichthys and Holoptychius; though, approached from the upper or Carboniferous direction, they might rather be assumed as the natural sandy base of that system into which they insensibly graduate. On the whole, they are remarkably barren of organic remains, though in some localities (Dura Den in Fife, Lauderdale) they have yielded a number of genera and species of fishes, crowded profusely through the pale sandstone, as if the individuals had been suddenly killed and rapidly covered over with sediment (see p. 1075). Among the characteristic organisms of the Scottish Upper Old Red Sandstone are Bothriolepis (Pterichthys) major, Holoptychius nobilissimus, H. Andersoni, Glyptopomus, Glyptolæmus and Phaneropleuron.

In the Upper Old Red Sandstone of the Firth of Clyde, Bothriolepis (Pterichthys) major and Holoptychius occur at the Heads of Ayr, while a band of marine limestone, lying in the red sandstone series in Arran, is crowded with ordinary Carboniferous Limestone shells, such as Productus giganteus, P. semireticulatus, P. punctatus, Chonetes hardrensis, Spirifer lineatus, etc. These fossils are absent from the great series of red sandstones overlying the limestone, and do not reappear till we reach the limestones in the Lower Carboniferous series; yet the organisms must have been living during all that long interval outside of the Upper Old Red Sandstone area (p. 1370). Not only so, but they must have been in existence long before the formation of the thick Arran limestone, though it was only during the comparatively brief interval represented by that limestone that geographical changes permitted them to enter the Old Red Sandstone basin and settle for a while on its floor. The higher parts of the Upper Old Red Sandstone seem thus to have been contemporaneous with a Carboniferous Limestone fauna which, having appeared beyond the British area, was ready to spread over it as soon as the conditions became favorable for the invasion. It is, of course, obvious that such an abundant and varied fauna as that of the Car-

boniferous Limestone cannot have come suddenly into existence at the period marked by the base of the limestone. It must have had a long previous existence outside the present area of the deposit.

In the north of Scotland, on the Lowlands bordering the Moray Firth, and again in the island of Hoy, one of the Orkney group, yellow and red sandstones (with interbedded diabase and tuff), containing characteristic Upper Old Red Sandstone fishes, lie unconformably upon the Caithness flags.[171] In these northern tracts, the same relation is thus traceable as in the central counties, between the two divisions of the system.

Turning southward across the border districts into the north of England, we find the red sandstones and conglomerates of the Upper Old Red Sandstone lying unconformably on Silurian rocks and Lower Old Red Sandstone. Some of the brecciated conglomerates have much resemblance to glacial detritus, and it was suggested by Ramsay that they have been connected with contemporaneous ice-action.[172] Such are the breccias of the Lammermuir Hills, and those which show themselves here and there from under the overlying mass of Carboniferous strata that flanks the Silurian hills of Cumberland and Westmoreland. Red conglomerates and sandstones appear interruptedly at the base of the Carboniferous rocks, even as far as Flintshire and Anglesey. They are commonly classed as Old Red Sandstone, but merely from their position and lithological character. No organic remains have been found in them. They may therefore, in part at least, belong to the Carboniferous system, having been deposited on different successive horizons during the gradual depression of the land. In Devonshire, at Barnstaple, Pilton, Marwood, and Baggy Point, certain sandstones, shales, and limestones (already referred to in the account of the Devonian rocks) graduate upward into the base of the Carboniferous system, and appear to represent the Upper Old Red Sandstone of the rest

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171 Trans. Roy. Soc. Edin. xxviii. 1878, p. 405; Quart. Journ. Geol. Soc. xlviii. 1892, Presidential Address, p. 100.

172 The examples of supposed glacial striæ in the pebbles in these breccias may be merely frictional markings connected with faults or internal movements of the rocks. But the forms of the pebbles, their moraine like unstratified or rudely-stratified accumulation, and the occurrence of aggregated lumps of breccia in the midst of fine sandstone strongly remind one of the familiar features of true glacial deposits. Compare H. Reusch, on similar evidence from the Palæozoic rocks of Norway, Norges Geol. Undersög. Aarbog. 1891.

of Britain. They contain land-plants and also many marine fossils, some of which are common Carboniferous forms. They thus indicate a transition into the geographical conditions of the Carboniferous period, as is still more clearly illustrated by the corresponding strata in Scotland.

The Old Red Sandstone attains a great development in the south and southwest of Ireland. The thick "Dingle-Beds" and "Glengariff grits" pass down into Upper Silurian strata, and no doubt represent the Lower Old Red Sandstone of Scotland. They are succeeded in Kerry by red sandstones which cover them unconformably, and resemble the ordinary Upper Old Red Sandstone of Scotland. In Cork and the southeast of Ireland they are followed by the pale sandstones and shaly flagstones known as the "Kiltorcan beds," with apparently a perfect conformability. The Kiltorcan beds (which pass up conformably into the Carboniferous Slate) have yielded a few fishes (Bothriolepis, Coccosteus, Pterichthys, Glyptolepis), some crustaceans (Belinurus, Pterygotus), a fresh-water lamellibranch (Anodonta Jukesii), and a number of ferns and other land-plants (Palæopteris, Sphenopteris, Sagenaria (Cyclostigma), Knorria.[173]

Norway, etc.—On the continent of Europe the Old Red Sandstone type can hardly be said to occur. Some outliers of red sandstone and conglomerate (p. 1324) in northern and western Norway reach a thickness of 1000 to 1200 feet. Near Christiania, they follow the Silurian strata like the Old Red Sandstone, but as yet have yielded no fossils, so that, as they pass up into no younger formation, their geological horizon cannot be certainly fixed. The Devonian rocks of Russia have been above referred to as presenting a union of the two types of this part of the geological series. The extension of the land of the Old Red Sandstone period, with its characteristic flora, far north within the Arctic Circle is indicated by the discoveries made at Bear Island (lat. 70° 30′ N.) between the coast of Norway and Spitzbergen. Certain seams of coal and coaly shale occur at that locality, underlying beds of Carboniferous Lime-

[173] Prof. Hull, Q. J. Geol. Soc. xxxv. xxxvi.; Trans. Roy. Dublin Soc. (new ser.) i. p. 135, 1880; Explanations of the Geol. Survey, Ireland, sheets 167, etc., 187, etc.; J. Nolan, Q. J. Geol. Soc. 1880, p. 529; Kinahan, Trans. Geol. Soc. Edin. 1882, p. 152. A recent personal examination has convinced me that the south of Ireland formed another of the basins in which the Lower Old Red Sandstone was accumulated.

stone and overlying some yellow dolomite, calcareous shale, and red shales. They have been assigned by Heer to the Carboniferous series, but are regarded by Dawson as unquestionably Devonian. They may be correlated with the Upper Old Red Sandstone of Britain. Heer enumerates eighteen species; only three are peculiar to the locality, while among the others are some widely-diffused forms: Calamites radiatus (transitionis), Palæopteris roemeriana, Sphenopteris Schimperi, Cardiopteris frondosa, Lepidodendron veltheimianum and three other species, Knorria imbricata, and Sagenaria (Cyclostigma) kiltorkensis."[174] In Spitzbergen itself, according to the researches of Nathorst, the so-called "Heckla-Hook formation" contains a large assemblage of fish-remains, shells, and plants, which prove it to be the equivalent of part of the Scottish Old Red Sandstone.

North America.—It is interesting to observe that in North America representatives occur of the two divergent Devonian and Old Red Sandstone types of Europe. The American Devonian facies has already been referred to. On the eastern side of the ancient pre-Cambrian and Silurian ridge, which, stretching southward from Canada, separated in early Palæozoic time the great interior basin from the Atlantic slopes, we find the Devonian rocks of New York, Pennsylvania, and the interior represented in New Brunswick and Nova Scotia by a totally different series of deposits. The contrast strikingly recalls that presented by the Old Red Sandstone of the north of Scotland and the Devonian rocks of North Germany. On the south side of the St. Lawrence, the coast of Gaspé shows rocks of the so-called "Quebec group" unconformably overlain by gray limestones with green and red shales, attaining, according to Logan, a total thickness of about 2000 feet,[175] and in some bands replete with Upper Silurian fossils. They are conformably followed by a vast arenaceous series of deposits termed the Gaspé Sandstones, to which the careful measurements of Logan and his colleagues of the Canadian Geological Survey assign a depth of 7036 feet. This formation consists of gray and drab-colored sandstones, with occasional gray shales and bands of massive conglomerate. Similar rocks reappear along the southern coast of New Brunswick, where

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[174] Heer, Q. J. Geol. Soc. xxviii. p. 161. Dawson, op. cit. xxix. p. 24.
[175] "Geology of Canada," p. 393.

they attain a depth of 9500 feet, and again on the opposite side of the Bay of Fundy. The researches of Sir J. W. Dawson, already referred to, have made known the remarkable flora of these rocks. Some of the same plants have been met with in the Devonian rocks to the west of the Archæan ridge, so that there can be little doubt of the contemporaneity of the deposits on the two sides. Besides the abundant vegetation, a few traces of the fauna of the period have been recovered from the Old Red Sandstone. Among them are the remains of several small crustaceans, including a minute shrimp-like Eurypterus, and the more highly organized Amphipeltis, with the snail (Strophites) referred to on p. 1318. That the sea had at least occasional access to the inland basins into which the abundant terrestrial vegetation was washed, is proved by the occurrence of marine organisms, such as a small annelid (Spirorbis) adhering to the leaves of the plants, and (in Gaspé and Nova Scotia) by the occasional appearance of brachiopods, especially Lingula, Spirifer, and Chonetes.[176]

Section iv. Carboniferous

§ 1. General Characters

This great system of rocks has received its name from the seams of coal which form one of its distinguishing characters in most parts of the world. Both in Europe and America it may be seen passing down conformably into the Devonian and Old Red Sandstone. So insensible indeed is the gradation in many consecutive sections where the two systems join each other that no sharp line can there be drawn between them. This stratigraphical passage is likewise in many places associated with a corresponding commingling of organic remains, either by the ascent of undoubted Devonian species into the lower parts of the Carboniferous series, or by the appearance in the Upper Devonian beds of species which attained their maximum development in Carbonifer-

[176] Dawson's "Acadian Geology," chaps. xxi. and xxii.

ous times. Hence there can be no doubt as to the true place of the Carboniferous system in the geological record. In some places, however, the higher members of this system are found resting unconformably upon Devonian or older rocks, so that local disturbances of considerable magnitude occurred before or at the commencement of the Carboniferous period. It is deserving of notice that Carboniferous rocks are very generally arranged in basin-shaped areas, many of which have been wholly or partially overspread unconformably by later formations. This disposition, so well seen in Europe, and particularly in the central and western half of the Continent, has in some cases been caused merely by the plication and subsequent extensive denudation of what were originally wide continuous sheets of rock, as may be observed in the British Isles. But the remarkable small scattered coal-basins of France and central Germany were probably from the first isolated areas of deposit, though they have suffered, in some cases very greatly, from subsequent plication and denudation. In Russia, and still more in China and western North America, Carboniferous rocks cover thousands of square miles in horizontal or only very gently undulating sheets.

Rocks.—The materials of which the Carboniferous system is built up differ considerably in different regions; but two facies of sedimentation have a wide development. In one of these, the marine type, limestones form the prevailing rocks, and are often visibly made up of organic remains, chiefly encrinites, corals, foraminifera, and mollusks. According to Dupont's researches in the Carboniferous Limestone of Belgium there are two main types of limestone: (1) the massive limestones formed by reef-building corals and coralloid animals, and disposed in fringing reefs or dis-

persed atolls, according to their nearness to or distance from the coast of the time; and (2) the detritic limestones, consisting either of an aggregation of crinoid stems or of coral-débris, and often stretching in extensive sheets like sandstone or shale.[177] The limestones of both types assume a compact homogeneous character, with black, gray, white, or mottled colors, and are occasionally largely quarried as marble. Local developments of oolitic structure occur among them. They also assume in some places a yellowish, dull, finely granular aspect and more or less dolomitic composition. They occur in beds, sometimes as in central England, Ireland, and Belgium, piled over each other for a depth of hundreds of feet, and in Utah for several thousand feet, with little or no intercalation of other material than limestone. The limestones frequently contain irregular nodules of a white, gray, or black flinty chert (phtanite), which, presenting a close resemblance to the flints of the chalk, occur in certain beds or layers of rock, sometimes in numbers sufficient to form of themselves tolerably distinct strata.[178] These concretions are associated with the organisms of the rock, some of which, completely silicified and beautifully preserved, may be found imbedded in the chert. Dolomite, usually of a dull yellowish color, granular texture, and rough feel, occurs both in beds regularly interstratified with the limestones and also in broad wall-like masses running through the limestones. In the latter cases, it is evident that the limestone has been changed into dolomite along lines of joint; in the former, the dolomite may be due to contemporaneous alteration of the original calcareous deposit

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[177] Bull. Acad. Roy. Belg. (3) v. 1883, No. 2.
[178] Renard, op. cit. (2) xlvi. p. 9.

by the magnesian salts of sea-water as already explained (pp. 546, 695). Traced to a distance, the limestones are often found to grow thinner, and to be separated by increasing thicknesses of shale, or to become more and more argillaceous and to pass eventually into shale. The shales, too, are often largely calcareous, and charged with fossils; but in some places assume dark colors, become more thoroughly argillaceous, and contain, besides carbonaceous matter, an impregnation of pyrites or marcasite. Where the marine Carboniferous type dies out, the shales may pass even into coal, associated with sandstones, clays, and ironstones. In Britain, abundant contemporaneous volcanic rocks are preserved in the Carboniferous Limestone series.

The second facies of sedimentation points to deposit in shallow lagoons, which at first were replenished from the sea, but afterward appear to have been brackish and then fresh, or in lakes into which coarse and fine detritus as well as vegetation and animal remains were washed from neighboring land. The most abundant strata of this type are sandstones, which, presenting every gradation of fineness of grain up to pebbly grits, and even (near former shore-lines) conglomerates, are commonly yellow, gray, or white in color, well-bedded, sometimes micaceous and fissile, sometimes compact; often full of streaks or layers of coaly matter. Besides the existence of pebbly grits and conglomerates pointing to comparatively strong currents of transport, there occur, in different parts of the Carboniferous system, scattered pieces and even blocks of granite, gneiss, quartzite, or other durable material which lie imbedded, sometimes singly, sometimes in groups, in limestone, sandstone, and in coal. Various explanations have been proposed to account for these erratics, some writers having even suggested the action

of drifting ice.[179] The stones were most probably transported by floating plants. Seaweeds with their rootlets wrapped round loose blocks might easily be torn up and drifted out to sea so as to drop their freight among corals and crinoids living on the bottom. But more usually trees growing on the land would envelop soil and stones among their roots, and if blown down and carried away by storms and floods might bear these with them.[180]

Next in abundance to the sandy sediment came the deposits of mud now forming shales. These occur in seams or bands from less than an inch to many yards in thickness. They are commonly black and carbonaceous, frequently largely charged with pyritous impregnations, sometimes crowded with concretions of clay-ironstone. Coal occurs among these strata in seams varying from less than an inch up to several feet or yards in thickness, but swelling out in some rare examples to 100 feet or more. A coal-seam may consist entirely of one kind of coal. Frequently, however, it contains one or more thin layers or "partings" of shale, the nature or quality of the seam being alike or different on the two sides of the parting. The same seam may be a cannel-coal at one part of a mineral field, an ordinary soft coal at a second, and an ironstone at a third. Moreover, in Britain and other countries, each coal-seam is usually underlain by a bed of fire-clay or shale, through which rootlets branch freely in all directions. These fire-clays, as their name denotes, are used for pottery or brick-making. They appear to be the soil on which the plants of the coal grew, and it

179 For remarks on the climate of the Carboniferous period see postea, p. 1340.

180 For accounts of these travelled stones in Carboniferous rocks see especially D. Stur, Jahrb. Geol. Reichsanst. xxxv. 1885, p. 613, and the authorities cited by him; also W. S. Gresley, Geol. Mag. 1885, p. 553; Quart. Journ. Geol. Soc. xliii. 1887, p. 734; V. Ball, op. cit. xliv. 1888, p. 371.

was doubtless the growth of the vegetation that deprived them of their alkalies and iron, and thus made them industrially valuable. In the small coal-basins of central France the coal is dispersed in banks and isolated veins all through the Carboniferous strata. Clay-ironstone occurs abundantly in some coal-fields, both in the form of concretions (sphærosiderite) and also in distinct layers from less than an inch to eighteen inches or more in thickness. The nodules have generally been formed round some organic object, such as a shell, seed-cone, fern-frond, etc. Many of the ironstone beds likewise abound in organic remains, some of them, like the "mussel-band" ironstone of Scotland, consisting almost wholly of valves of Anthracosia or other shell converted into carbonate of iron.

The mode of origin of coal cannot be closely paralleled by any modern formation, and various divergent views have been expressed on the subject. There seem to have been two distinct modes of accumulation, (1) by growth *in situ*, and (2) by drifting from adjacent land. It is possible that in some coal-fields both these processes may have been successively or simultaneously in operation, so that the results are commingled.

1. In those cases where the evidence points to growth *in situ*, the coal-seams have been laid down with tolerable uniformity of thickness and character over considerable areas of ground, and they now appear as regular layers intercalated between sheets of sediment and for the most part rest on fire-clay or shale, into which the stigmaria rootlets may frequently be seen to ramify as in the position of growth.[181]

[181] For arguments in support of the view that coal was formed of plants *in situ* see Logan, Trans. Geol. Soc. vi. 1842, p. 491. Newberry, Amer. Journ. Sci. xxiii. 1857, p. 212, "Geol. Surv. Ohio," vol. ii. Geology, p. 125; Gümbel, Sitzb. Bayer. Akad. 1883.

The nearest analogy to these conditions is probably furnished by cypress swamps[182] or the mangrove swamps alluded to already (p. 806), where masses of arborescent vegetation, with their roots spreading in salt water among marine organisms, grow out into the sea as a belt or fringe on low shores, and form a matted soil which adds to the breadth of the land. The coal-growths no doubt also flourished in salt water; for such shells as Aviculopecten and Goniatites are found lying on the coal or in the shales attached to it. Each coal-seam represents the accumulated growth of a period which was limited either by the exhaustion of the soil underneath the vegetation (as may be indicated by the composition of the fire-clays), or by the rate of the intermittent subsidence that affected the whole area of coal-growths. Though the vegetation in these coal-fields may have grown as a whole *in situ*, there may also have been considerable transport of loose leaves, branches, trunks, etc., after storms, and also during times of more rapid subsidence. From the fact that a succession of coal-seams, each representing a former surface of terrestrial vegetation, can be seen in a single coal-field extending through a vertical thickness of 10,000 feet or more, it is clear that the strata of such a field must have been laid down during prolonged and extensive subsidence. It has been assumed that, besides depression, movements in an upward direction were needful to bring the submerged surfaces once more up within the limits of plant growth. But this would involve a prolonged and almost inconceivable see-saw oscillation; and the assumption is really unnecessary if we suppose that the downward

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[182] For an account of the submerged lands of the Mississippi, see Lyell's "Second Visit to the United States," chap. xxxiii.

movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting-up of lagoons and the spread of coal-jungles.[183]

2. The researches of Grand' Eury, Fayol, and others in the small coal-basins of central France have shown that in these regions much vegetable matter was washed down from adjacent land.[184] The coal is irregularly distributed among the strata, and it is associated with beds of coarse detritus and other evidence of torrential action. Numerous trunks of calamododendra, sigillariæ, and other trees imbedded in the sandstones and shales vertically and at all angles of inclination bear witness, like the "snags" of the Mississippi, to the currents that transported them. The basins in which the accumulated detritus and vegetation were entombed seem to have been small, but sometimes comparatively deep lakes lying on the surface of the crystalline rocks that formed an uneven land-surface during the Carboniferous period in the heart of France. But there is evidence, even in these basins, of the growth of coal-plants *in situ*, and of the gradual subsidence of the alluvial floors on which they took root. Grand' Eury has shown the existence of tree-trunks with their roots in place on many successive levels, and has further ascertained that these trees, as they were enveloped in sediment, pushed out rootlets at higher levels into the silt that gathered round them.

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[183] See a statement of the oscillation theory as far back as 1849 by M. Virlet d'Aoust, Bull. Soc. Geol. France (2) vi. p. 616.

[184] For the detrital origin of coal, see Grand' Eury, Ann. des Mines, 1882 (i.) pp. 99–292; Mem. Soc. Geol. France, 3e ser. iv. 1887; "Geol. et Paléontol. du bassin Houiller du Gard," 1891. Fayol, "Études sur le Terrain Houiller de Commentry," part 1. Bull. Soc. Industrie Min. ser. 2, vol. xv. and Atlas, 1887. Bull Soc. Geol. France, 3e ser. xvii. 1888; B. Renault, "Flore Fossile de Commentry," Bull. Soc. Hist. Nat. d'Autun, 1891. A. de Lapparent, Rev. Quest. Scien. July, 1892.

It would thus appear that no one hypothesis is universally applicable for the explanation of the origin of coal, but that growth on the spot and transport from neighboring land have both in different regions contemporaneously and at successive periods come into play.

In this place reference may most conveniently be made to the probable climate in which these geological changes took place. The remarkable profusion of the vegetation of the Carboniferous period, not only in the Old World but in the New, suggested the idea that the atmosphere was then much more charged with carbonic acid than it now is. Undoubtedly there has been a continual abstraction of this gas from the atmosphere ever since land-plants began to live on the earth's surface, and it is allowable to infer that the proportion of it in the air in Palæozoic time may have been somewhat greater than now. But the difference could hardly have been serious, otherwise it seems incredible that the numerous insects, labyrinthodonts and other air-breathers, could have existed. Most probably the luxuriance of the flora is rather to be ascribed to the warm moist climate which in Carboniferous times appears to have spread over the globe even into Arctic latitudes. On the other hand, evidence has been adduced to support the view that in spite of the genial temperature indicated by the vegetation there were glaciers even in tropical and sub-tropical regions. Coarse bowlder-conglomerates and striated stones have been cited from various parts of India, South Africa, and Eastern Australia, as evidence of ice-action. There appears, however, to be some element of doubt as to the interpretation of the facts adduced. It may be matter for consideration whether the bowlder-beds could not be accumulated by torrential waters, and whether the striated surfaces on the

stones might not have been produced by internal movements in the rocks, like slickensides (p. 878).[185]

LIFE.—Each of the two facies of sedimentation above described has its own characteristic organic types, the one series of strata presenting us chiefly with the fauna of the sea, the other mainly with the flora of the land. The marine fauna is specially rich in crinoids, corals, and brachiopods, which of themselves constitute entire beds of limestone. Among the lower forms of life the foraminifera are well represented. The genera include Amphistegina, Archæodiscus, Climacammina, Endothyra, Lagena, Saccammina, Fusulina, Trochammina, and Valvulina. Some of these genera exhibit a wide geographical range; Saccammina, for example, forms beds of limestone in Britain and Belgium, and Fusulina plays a still more important part in the Carboniferous Limestone of the region from Russia to China and Japan, as well as in North America; one species of Valvulina (V. palæotrochus) extends from Ireland to Russia on the one side and to North America on the other. As already noticed, species of organisms, with a wide geographical extension, have also a long geological range, and this is more specially exemplified in such lowly grades of existence as the foraminifera. Trochammina incerta, for instance, is found through the whole Carboniferous Limestone series of England, reappears in the Magnesian Limestone of the Permian system, and occurs not only in Britain but in Germany and Russia.[186] The

[185] The glacial origin of the phenomena in question has been ably advocated by Mr. W. T. Blanford, "Manual of Geology of India," Address to Geological Section of British Association, Montreal; and H. F. Blanford, Quart. Journ. Geol. Soc. xxxi. 1875, p. 519. Sutherland, op. cit. xxvi. p. 514; W. Waagen, Jahrb. Geol. Reichsanst. xxxvii. 1887, p. 143. A. Julien has advocated the glacial origin of the coarse Carboniferous breccias of Central France. Compt. Rend. cxvii. 1893, p. 255.

[186] H. B. Brady, "Monograph of Carboniferous and Permian Foraminifera," Palæontog. Soc. 1876.

corals (Fig. 353) are represented by tabulate (Favosites, Michelinia, Alveolites, Chætetes), and still more by rugose forms (Amplexus, Zaphrentis, Cyathophyllum, Aulophyllum, Clisiophyllum, Lithostrotion, Lonsdaleia, Phillipsas-

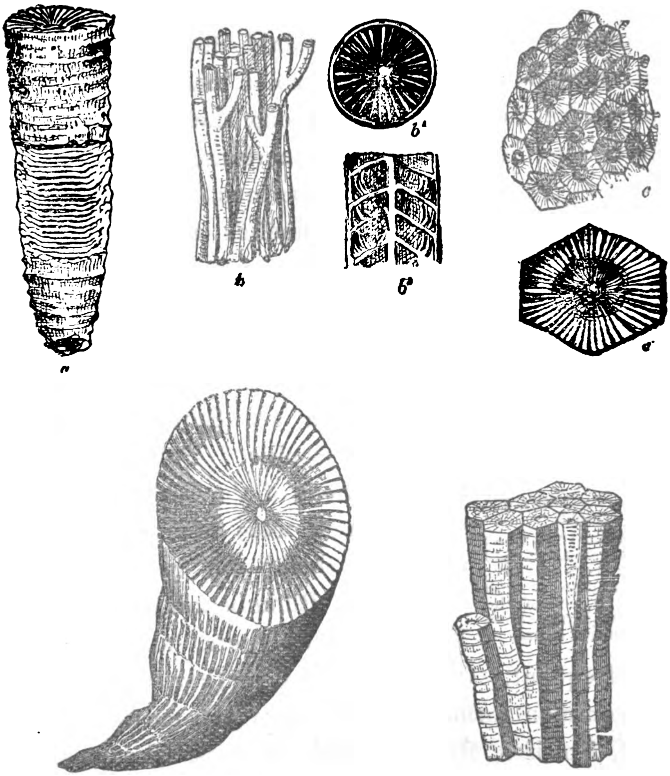

Fig. 353.—Carboniferous Corals.

a, Zaphrentis cylindrica, Scoul.; b, Lithostrotion junceum, Flem., b1, Do. magnified, transverse section, b2, Do. magnified, longitudinal section; c, Lithostrotion Portlocki, Milne Edw., c1, Do. calyx magnified; d, Cyathophyllum Stutchburyi, Milne Edw.; e, Lithostrotion basaltiforme, Phill., sp.

træa). The Echinoderms were more abundant and varied in this than in any other geological period. Thus among the urchins of the Carboniferous seas were species of

Archæocidaris, Palæchinus, and Melonites. The blastoids or pentremites, which now took the place in Carboniferous waters that in Silurian times had been filled by the cystideans, attained their maximum development. But it was the order of crinoids that chiefly swarmed in the seas where the Carboniferous Limestone was laid down, their separated joints now mainly composing solid masses of rock several hundred feet in thickness. Among their most conspicuous genera were Platycrinus, Actinocrinus, Cyathocrinus (Fig. 354), Poteriocrinus, and Rhodocrinus. Tubicolar annelids abounded, some of the species being solitary and attached to shells, corals, etc., others occurring in small clusters and some in gregarious masses forming beds of limestone. The chief genera are Spirorbis, Serpulites, Ortonia, Vermilia. Polyzoa abound in some portions of the Carboniferous Limestone, which were almost entirely composed of them, the genera Fenestella, Ceriopora, Rhombopora, Sulcoretepora, Vincularia, Polypora, and Glauconome being frequent. Of the brachiopods (Fig. 355) some of the most common forms are Productus (the most characteristic genus), Spirifer, Rhynchonella, Athyris, Chonetes, Orthis, Terebratula, Lingula, and Discina.[187] Among these are species

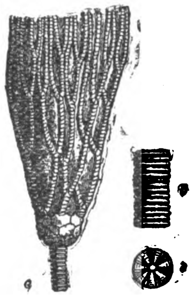

Fig. 354.—Carboniferous Crinoid. Cyathocrinus planus; *a*, calyx, arms and upper part of stem; *b*, portions of the stem; *c*, one of the column-joints showing central canal.

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[187] Productus is almost wholly Carboniferous, and in the species P. giganteus of the Carboniferous Limestone reached the maximum size attained by the brachiopods, some individuals measuring eight inches across. Other genera had already existed a long time; some even of the species were of ancient date—Orthis resupinata of the Carboniferous Limestone and the Devonian O. striatula and Strophomena depressa had survived, according to Gosselet, from the time of the Bala beds of the Lower Silurian period. (Gosselet, Esquisse, p. 118.)

that appear to range over the whole world, such as Productus semireticulatus, costatus, longispinus, pustulosus, cora, aculeatus, undatus; Streptorhynchus crenistria; Spirifer lineatus, glaber; Athyris globularis; and Terebratula hastata. The higher mollusks now begin to preponderate over the brachiopods. The lamellibranchs (Fig. 356) include forms of Aviculopecten, Posidonomya, Leda, Nucula, Sanguinolites, Lep-

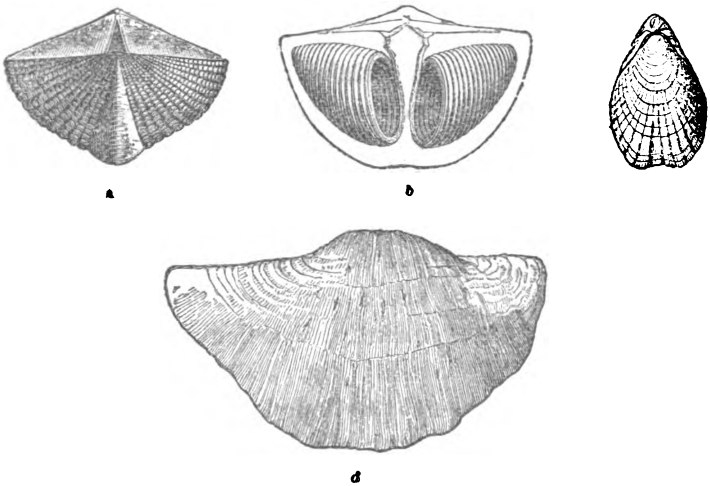


Fig. 355.—Carboniferous Brachiopods.

a, Spirifer hystericus, Schloth.; *b*, Do. interior of dorsal valve, showing spiral calcareous supports for the arms; *c*, Terebratula hastata, Sow.; *d*, Productus giganteus, Martin.

todomus, Schizodus, Edmondia, Anthracosia, Modiola, and Conocardium. The gasteropods (Fig. 357) are represented by numerous genera, among which Euomphalus, Natica, Pleurotomaria, Macrocheilus, and Loxonema are frequent. The genus Bellerophon is represented by many species, among which B. Urei and B. decussatus are frequent. The most abundant pteropod genus is Conularia (Fig. 358), which often attains a length of several inches. Of the cephalopods

(Fig. 359), the most abundant and widely distributed are forms of Orthoceras, Cytoceras, Nautilus, Discites, and Goniatites.

The crustacea present a facies very distinct from that of the previous Palæozoic formations. Trilobites now almost wholly disappear, only four genera of small forms (Proetus, Griffithides, Phillipsia, Brachymetopus) being left. But other crustacea are abundant, especially ostracods (Bairdia, Cypridellina, Cythere, Kirkbya, Leperditia, Beyrichia), which crowd many of the shales and sometimes even form seams of limestone. Some schizopod forms are met with (Palæocaris) and a few macrura occur not infrequently, particularly Anthrapalæmon (Fig. 360) and Palæocrangon (Crangopsis), also several phyllopods (Dithyrocaris, Ceratiocaris, Estheria, Leaia), with the larger merostomatous Eurypterus and king-crabs (Prestwichia, Belinurus). The Carboniferous Limestone of the British Isles has supplied somewhere about 100 genera of fishes, chiefly represented

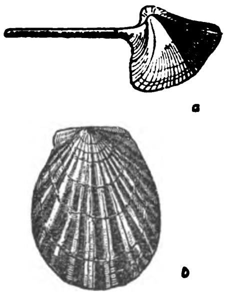


Fig. 356.
Carboniferous Lamellibranchs.
a, Conocardium aliforme, Sow.; *b*, Aviculopecten sublobatus, Phill., showing color-bands.

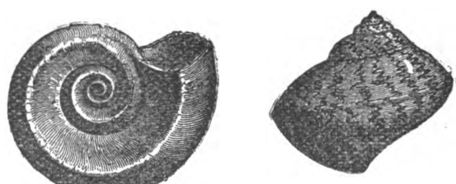


Fig. 357.—Carboniferous Gasteropods.
a, Euomphalus pentangulatus, Sow.; *b*, Pleurotomaria carinata, Sow., showing color-bands.

by teeth and spines (Psammodus, Cochliodus, Cladodus, Petalodus, Ctenodus, Rhizodus, Ctenoptychius, etc.). Some of these were no doubt selachians which lived solely in the sea, but many, if not all, of the ganoids probably migrated

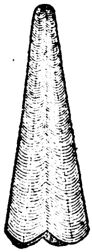


Fig. 358.
Carboniferous Pteropod.
Conularia quadrisulcata, Sow.

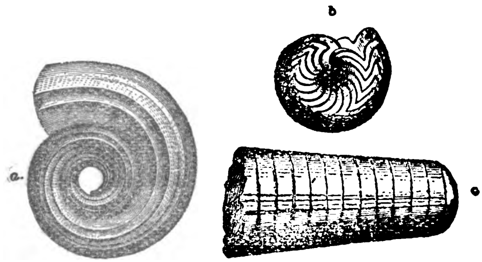


Fig. 359.—Carboniferous Cephalopods.
a, Nautilus (Discites) Koninckii, D'Orb.; b, Goniatites crenistria, Phill.; c, Orthoceras (Breynii, Mart.; laterale, Phill.)

between salt and fresh water; at least their remains are found in Scotland not only in marine limestones, but also in strata full of land-plants, cyprids, and other indications of estuarine or fluviatile conditions. Some of the fishes met

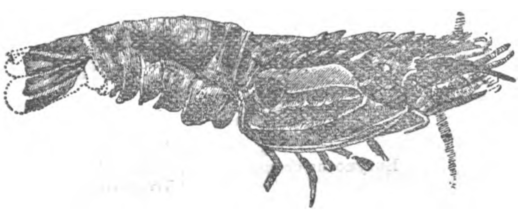


Fig. 360.—Carboniferous Macrourous Crustacean.
Anthrapalæmon Etheridgii, Peach, twice nat. size.

with in the plant-bearing type of the Carboniferous system are mentioned on p. 1357, together with the air-breathers and other terrestrial organisms.

It is deserving of remark that in the marine type of the Carboniferous system considerable differences may be ob-

served between the fossils of the limestones and the shales even in the same quarry. The limestones, for example, may be crowded with the joints of crinoids, corals of various kinds, producti and other brachiopods, while the shales above them may contain

Fig. 361.—Carboniferous Ichthyodorulite, or Dorsal Fish-spine. Sphenacanthus (Ctenacanthus) hybodoides, Egerton.

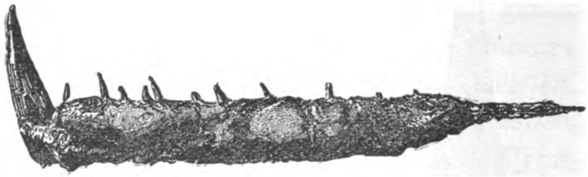


Fig. 362.—Carboniferous Fish.
Jaw of Rhizodus Hibberti, Ag. sp., one-third nat. size.

few of these organisms, but afford polyzoa, Conularia, horny brachiopods (Lingula, Dis-

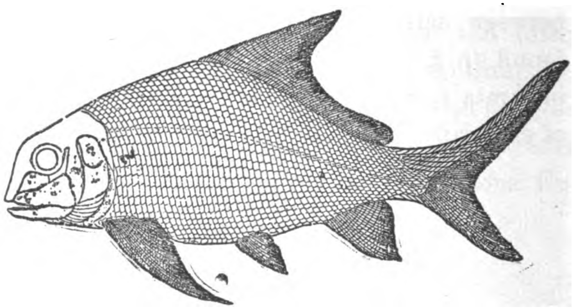


Fig. 363.—Carboniferous Fish.
Eurynotus crenatus, Ag., "Cement-stones" of Scotland (after Traquair).

cina), many lamellibranchs, especially pectens, aviculopectens, nuculas, ledas, and gasteropods (Pleurotomaria, Loxonema, Bellerophon, etc.). It is evident that while some organisms flourished only in clear water, such as that in which the limestones accumulated, others abounded on a muddy bottom, although some seem to have lived in either situation, if we may judge from

finding their remains indifferently in the calcareous and the muddy deposits.

The second phase of sedimentation, that of the coal-swamps, is marked by a very characteristic suite of organic

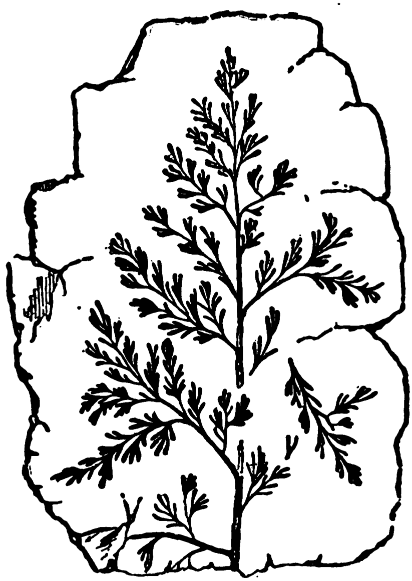


Fig. 364.—Carboniferous Fern.
Sphenopteris affinis, Lindl. and Hutt.

remains. Most abundant of these are the plants, which possess a special interest, inasmuch as they form the oldest terrestrial flora that has been abundantly preserved.[188] This

[188] On the Carboniferous flora, consult A. Brongniart, "Prodrome d'une Histoire des Vegetaux fossiles," 1828; Lindley and Hutton, "Fossil Flora of Great Britain," 1831–37. C. E. Weiss, "Fossile Flora d. jüngsten Steinkohl im Saar-Rhein-Geb," Bonn, 1869–72. "Die Flora d. Steinkohlen Formation," Berlin, 1881. Williamson's Memoirs "On the Organization of the Plants of the Coal-Measures," Phil. Trans. clxii. 1872, and subsequent volumes. Zeiller, on the Carboniferous flora of Valenciennes, Autun and Brive, in the series of volumes entitled "Études des Gites Mineraux de la France," published by the Ministry of Public Works; Zeiller and Renault on Fossil Flora of Commentry, Bull. Soc. Indust. Min. St. Etíenne, 2 vols. with Atlas, 1888–90. R. Kidston, Trans. R. S. Edin. xxxv. *et seq.*

flora is marked by a singular monotony of character all over the world, from the Equator into the Arctic Circle, the same genera, and sometimes even the same species, appearing to have ranged over the whole surface of the globe. It consisted almost entirely of vascular cryptogams, and pre-eminently of Equisetaceæ, Lycopodiaceæ, and Ferns. Though referable to existing groups, the plants presented many remarkable differences from their living representa-

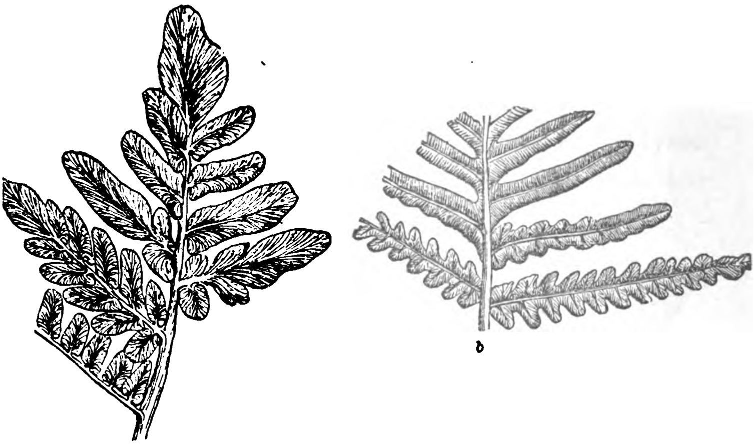


Fig. 365.—Carboniferous Ferns.
a, Neuropteris Loshii, Brongn.; *b*, Alethopteris Gibsoni, Lesq.

tives. In particular, save in the case of the ferns, they much exceeded in size any forms of the present vegetable world to which they can be assimilated. Our modern horse-tails had their allies in huge trees among the Carboniferous jungles, and the familiar club-moss of our hills, now a low creeping plant, was represented by tall-stemmed Lepidodendra that rose fifty feet or more into the air. The ferns, however, present no such contrast to forms still living. On the contrary, they often recall modern genera, which they

resemble not merely in general aspect, but even in their circinnate vernation and fructification. With the exception of a few tree-ferns, they seem to have been all low-growing plants, and perhaps were to some extent epiphytic upon the larger vegetation of the lagoons. Some of the more common

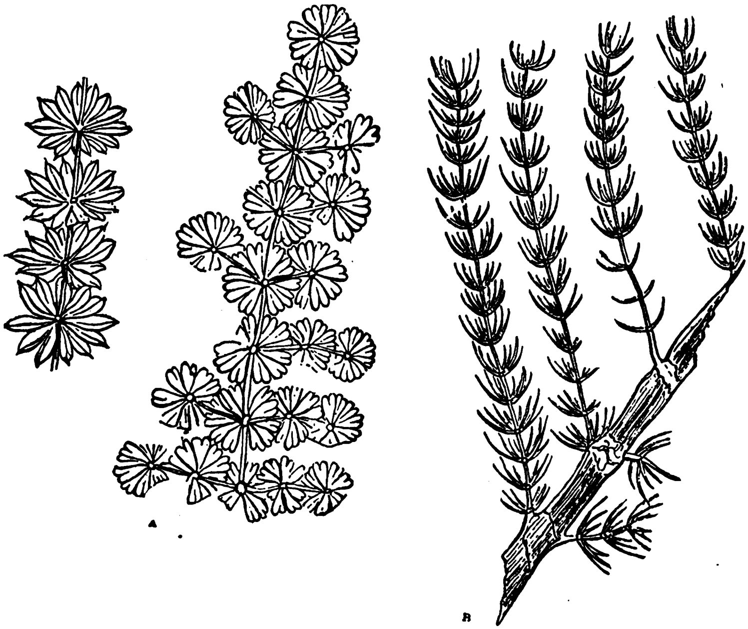


Fig. 366.—A, Annularia sphenophylloides; B, Asterophyllites.

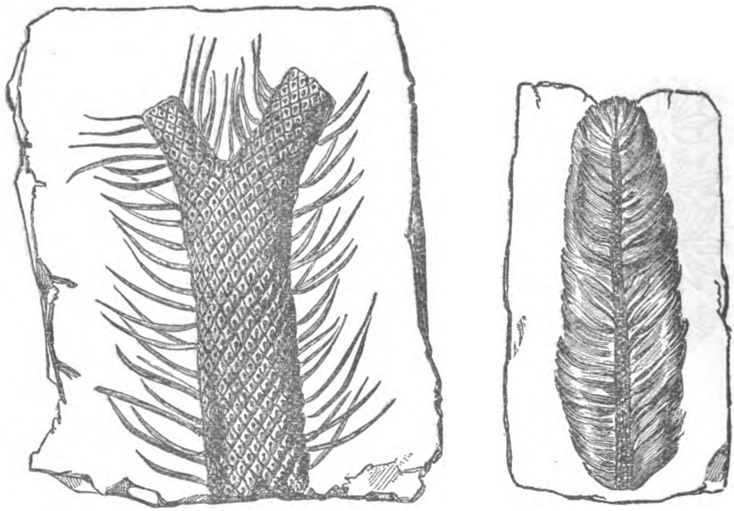
genera are Sphenopteris, Neuropteris, Cyclopteris, Odontopteris, Pecopteris, Alethopteris.[189]

Among the Equisetaceæ,[190] the genus Calamites is specially abundant. It usually occurs in fragments of jointed and finely-ribbed stems. From the rounded or blunted

[189] For an essay on the morphology and classification of the Carboniferous ferns see D. Stur, Sitzb. Akad. Wien. lxxxvi. 1883.

[190] On Carboniferous Calamaries, consult Weiss, Abh. Geol. Specialkarte Preussen, v.

base of the stem, other stems budded, and numerous rootlets proceeded, whereby the plants were anchored in the mud or sand of the lagoons, where they grew in dense thickets. According to Sir J. Dawson they seem to have fringed the great jungles of Sigillariæ, and to have acted as a filter that cleared the water of its sediment and prevented the vegetable accumulations of the coal-swamps



a *b*

Fig. 367.—Carboniferous Lycopods.
a, Lepidodendron ($\frac{1}{4}$); *b*, Lepidostrobus, nat. size.

from admixture with muddy sediment. To the foliage of Calamites different generic appellations have been attached (Fig. 366). The name Asterophyllites (Calamocladus) is given to jointed and fluted stems with verticils of slim branches proceeding from the joints and bearing whorls of long, narrow, pointed leaves. In Sphenophyllum the leaves were fewer in number and wedge-shaped; in Annularia, the close-set leaves were united at the base. Calamodendron is believed by some botanists to be the cast of the

pith of a woody stem belonging to some unknown tree, by others it is regarded as only a condition of the preservation of Calamites. Some fruits, supposed to belong to the calamaries, have been met with. Pothocites has been referred to Asterocalamites, Stachannularia seems attached to Annularia, while others known as Calamostachys and Macrostachys, are probably the fructification of calamites.

The Lycopods (Fig. 367) were represented by numerous species of the genus Lepidodendron, distinguished by the

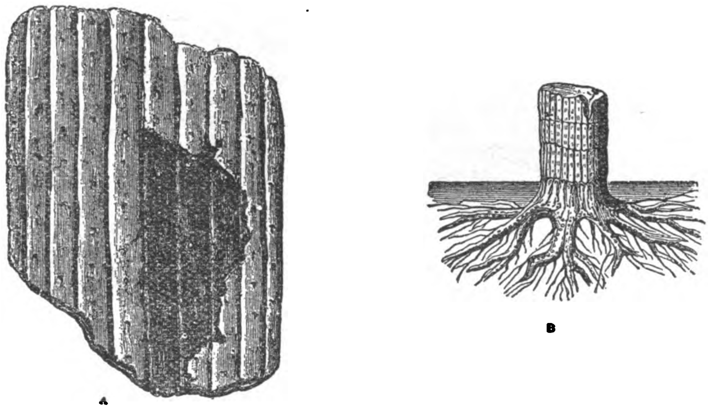


Fig. 368.—A, Sigillaria; portion of decorticated stem; B, Sigillaria stem terminating in Stigmaria Roots and rootlets.

quincuncial leaf-scars on its dichotomous stem. Its branches, closely covered with pointed leaves, bore at their ends cones or spikes (Lepidostrobus) consisting of a central axis, round which were placed imbricated scales, each carrying a spore-case. Other conspicuous genera were Ulodendron, Knorria, Lepidophloios, Halonia, Cyclocladia.

Among the most remarkable trees of the Carboniferous forests were the Sigillarioids, which are believed to have been akin to the Lepidodendra. The genus Sigillaria was distinguished by the great height (50 feet or more) of its

trunk, which sometimes measured five feet in diameter. Its stem was fluted (Fig. 368), and marked by parallel perpendicular lines of leaf-scars, but as it grew these external markings were lost. The base of the stem passes into the roots known as Stigmaria, the pitted and tuberculed stems of which are such common fossils (Figs. 368 B, 369). There can be little doubt, however, that Stigmaria was a form of root common to more than one kind of tree. The genus Cordaites belonged to a type of tree which by

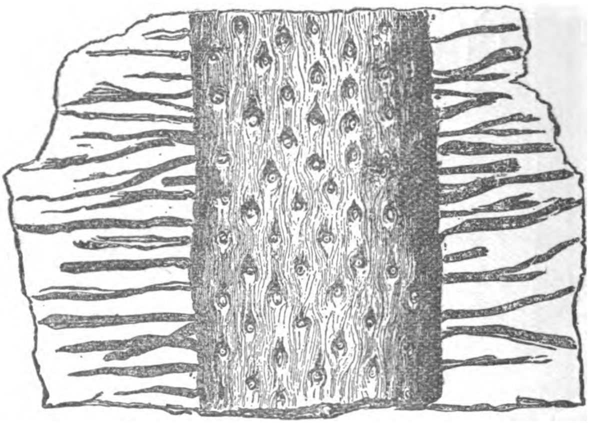


Fig. 369.—Stigmaria with attached rootlets.

some botanists has been placed among the cycads, by others among the conifers. It attained a great profusion in the time of the Coal-measures. Shooting up to a height of 20 or 30 feet, it carried narrow or broad, parallel-veined leaves, somewhat like those of a Yucca, which were attached by broad bases at somewhat wide distances to the stem, and on their fall left prominent leaf-scars. It bore catkins (Antholithus) which ripened into berries not unlike those of Yews (Cardiocarpus) (Fig. 371). Both of these forms of fructification occur in great abundance in some

bands of shale. True Coniferæ were probably abundant on the drier ground, for their stems (Dadoxylon, Araucarioxylon, Pinites) have been met with, particularly in the tuffs of ancient volcanic cones, on which they no doubt grew, and in sandstone, where they occur as driftwood, perhaps from higher ground (Fig. 370). It should be remembered that the flora preserved in the Carboniferous rocks is essentially that of the low grounds and swamps. The fruit

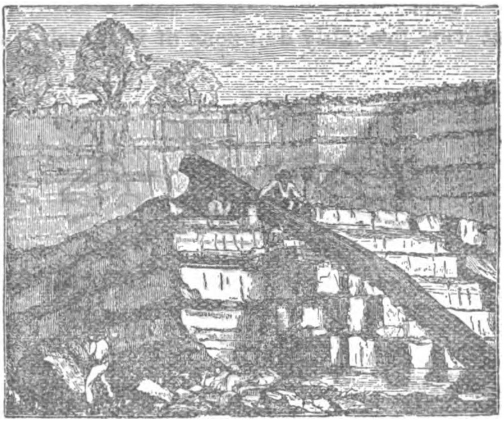


Fig. 370.—Coniferous Tree-trunk imbedded in Sandstone, Craigleith, Edinburgh (after Witham).

known as Trigonocarpus is supposed to be coniferous, somewhat like the fruit of the living Salisburia. That true monocotyledons existed in the Carboniferous period was until recently supposed to be proved by the discovery of a number of spikes, referred to the living order of Aroideæ (Pothocites), in the lower part of the Carboniferous system of Scotland; but Mr. R. Kidston has shown that the specimens are almost certainly the fructification of Bornia, a genus of Calamite.[191]

[191] Ann. Mag. Nat. Hist. May, 1883, p. 297.

The animal remains in the coal-bearing part of the Carboniferous rocks are comparatively few. As already stated, in certain bands of shale, coal, and ironstone in the lower half of the Coal-measures, undoubted proofs of the presence of the sea are afforded by the occurrence of some of the familiar shells of the Carboniferous Limestone. But toward the upper part of the Coal-measures, where these marine forms almost entirely disappear (among their last representatives being species of Lingula and Discina), other mollusks, that were probably denizens of brackish if not of fresh

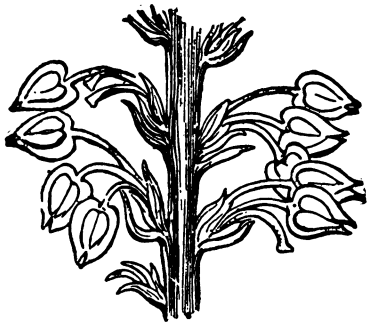


Fig. 371.—Antholite with Cardiocarpus.

water, occur in abundance. Among the more frequent are Anthracomya, Anthracosia, and Anthracoptera. Crustaceans are chiefly represented by Beyrichia, and Estheria, but large eurypterid forms likewise occur. Fishes are found frequently, remains of the larger kinds usually appearing in scales, teeth, fin-spines, or bones, while the smaller ganoids are often preserved entire. Common genera are Ctenodus, Strepsodus, Cheirodus (Fig. 372), Mesolepis, Ctenacanthus, Gyracanthus, Pleuracanthus, Ctenoptychius, and Megalichthys.

The presence of true air-breathers among the jungles of

the Carboniferous period has been established by the discovery of numerous specimens of arachnids, insects, myriapods, and labyrinthodonts. According to the latest census of Mr. Scudder there were known up to 1890 no fewer than 75 species of Carboniferous arachnids.[192] Scorpions (Eoscorpius) have been found both in Europe and America, and recently have been obtained in great numbers, in excellent preservation and of gigantic size, in the Lower Carboniferous rocks of Scotland (Fig. 373). Other arachnids occur, including

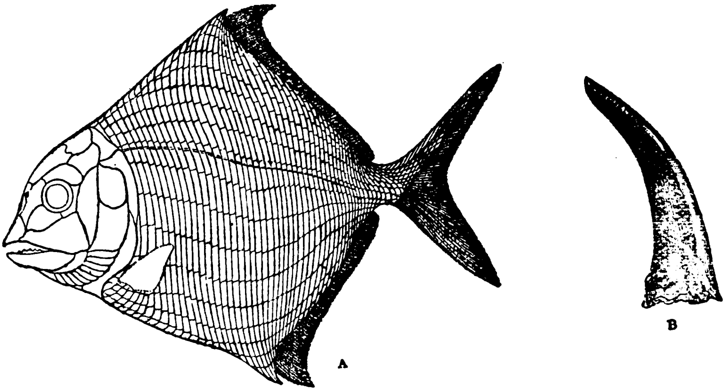


Fig. 372.—Coal-measure Fishes.
A, Cheirodus granulosus, Young, after Traquair; B, tooth of Strepsodus sauroids, Binney, sp.

ancient forms of spider (Protolycosa). Myriapods, of which upward of 40 species have been determined, were represented by various plant-eating millipeds (Xylobius, Archiulus, Iulus, Euphoberia). True insects likewise flitted through these dense jungles, and during the last ten years the number of species detected has been so large that no fewer than 239 species of orthoptera, 109 of neuroptera, 17 of hemiptera, and 11 of coleoptera have been obtained. Though their remains have been but scantily preserved,

[192] Bull. U. S. Geol. Surv. No. 71, 1891.

we know that they included ancient forms of mayfly, cockroach, cricket, and beetle. It is remarkable that from some coal-fields hardly a single trace of insect life has been obtained, while in others great numbers of specimens have been brought to light. A remarkable variety of forms has been found in the Saarbrück Coal-field; but perhaps the greatest number of individual specimens has come from that of Commentry, which up to the end of the year 1884 is computed to have furnished not less than 1300 individuals.

Fig. 373.—Carboniferous Scorpion. Eoscorpius glaber (B. N. Peach), Lower Carboniferous, Eskdale, Scotland.

Some of the insects were of considerable size. Thus the neuropterous Archæoptilus from the Derbyshire Coal-field had a spread of wing of perhaps fourteen inches or more; and a species of Dictyoneura (D. Monyi) had a wing about twelve inches in length. Others were remarkable for the vividness of their coloring (Brodia), the markings of which are still recognizable in the fossil specimens. One of the most singular features yet observed among these ancient insects is the union in the same individual of types of structure which are now entirely distinct. M. Ch. Brongniat has recently shown that wings which were admittedly neuropterous, and were referred to the genus Dictyoneura, were really attached to bodies which are unquestionably orthopterous.[193]

[193] Ch. Brongniart, Bull. Soc. Geol. France (3), xi. p. 142; also Scudder, Geol. Mag. 1881, p. 293; Mem. Boston. Soc. Nat. Hist. iii. 1883, p. 213; Proc. Amer. Acad. 1884, p. 167; Bull. U. S. Geol. Surv. Nos. 31 and 71. H. Woodward, Q. J. Geol. Soc. 1872, p. 60. The student interested in the study of fossil insects will find Mr. Scudder's Bibliography of the subject, Bull. U. S. Geol. Surv. No. 71, 1890, a valuable book of reference.

The Labyrinthodonts which appeared in Carboniferous times as the magnates of the vertebrate world had a salamander-like body with relatively weak limbs and a long tail. Sometimes the limbs seem to have been undeveloped, so that the body was serpent-like. The head was protected by bony plates, and there was likewise a ventral armor of integumentary scales. The British Carboniferous rocks have yielded about 20 genera (Anthracosaurus, Loxomma, Ophiderpeton, Pholiderpeton, Pteroplax, Urocordylus, etc.). These were probably fluviatile animals of predaceous habits, living on fish, crustacea, and other organisms of the fresh or salt waters of the coal-lagoons. The larger forms are believed to have measured 7 or 8 feet in length; some of the smaller examples, though adult and perfect, do not exceed as many inches.[194] The coal-field of Bohemia, which may be in part Permian, has likewise furnished a considerable number of genera and species of Labyrinthodonts and fishes.[195] The terrestrial fauna obtained from the interior of fossil trees in the Coal-measures of Nova Scotia includes land-shells of which several genera are now known (Dendropupa,[196] Pupa, Anthracopupa, Zonites, and Dawsonella).

Fossil plants do not serve so well for purposes of geological classification as fossil animals (pp. 1081, 1096, 1110). In the Saxon Coal-field, however, Geinitz (1856) distinguished five zones, each characterized by its own facies of vegetation. 1st. The Culm with Lepidodendron veltheimianum, Calamites transitionis, followed by the remaining four zones, which comprise the productive coal-measures; viz. 2d, the

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[194] Miall, Brit. Assoc. 1873, 1874.

[195] C. Feistmantel, Archiv. Naturw. Landesdurchforsch. Böhmen. v. No. 3, 1883, p. 55; A. Fritsch, "Fauna der Gaskohle Böhmens," 1879 and subsequent years.

[196] J. W. Dawson, Phil. Trans. vol. 173, 1882, p. 621.

zone of Sigillarias; 3d, the zone of Calamites; 4th, the zone of Annularia; and 5th, the zone of Ferns.[197] More recently Grand' Eury has subdivided the Carboniferous system of central France into the following members, according to the succession of vegetation:[198]

Supra-Carboniferous Flora, simpler and less rich than that below, showing a passage into the Permian flora above, characterized by a rapid diminution of Alethopteris, Odontopteris xenopteroides, Dictyopteris, Annularia, Sphenophyllum. The Calamites are represented by abundant individuals of C. varians and C. Suckowii, also Asterophyllites equisetiformis; the ferns by Pecopteris cyatheoides, P. hemitelioides, Odontopteris minor, O. Schlotheimii, several species of Neuropteris, etc.; the Sigillarias by S. Brardii, S. spinulosa, and Stigmaria ficoides; Cordaites by numerous narrow-leaved forms; the Calamodendra by a prodigious abundance of some species, *e.g.* Calamodendron bistriatum, Calamites cruciatus, Arthropitus subcommunis; the conifers by Walchia piniformis and some others.

Upper Coal Flora (properly so called).—Calamites often abundant—C. interruptus, C. Suckowii, C. cannæformis, Asterophyllites hippuroides, Macrostachya infundibuliformis (very common), Annularia brevifolia, and A. longifolia (common throughout), Sphenophyllum oblongifolium. Ferns richly developed, particularly of the genera Pecopteris (P. unita, arguta, polymorpha, and especially Schlotheimii); Odontopteris (O. reichiana, Brardii, mixoneura, xenopteroides, the last extremely abundant); Caulopteris macrodiscus, Alethopteris Grandini in great profusion, Callipteridium (C. ovatum, gigas, densifolia, common). Lepidodendra have almost disappeared; Sigillariæ are not uncommon (S. rhitydolepis, S. Brardii), with Stigmariopsis and Syringodendron. Cordaites occurs in great abundance; the conifers are represented by Walchia piniformis and a few other species. Calamodendra occur in great abundance, especially Calamites cruciatus.

Upper Coal Flora—(Lower Zone, Flore du terrain houiller sous-supérieure).—Calamites and Asterophyllites

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197 "Geognost. Darst. Steink. Sachsen," 1856, p. 83; "Die Steinkohlen Deutschlands," 1865, i. p. 29.

198 "Flore Carbonifere du Departement de la Loire et du Centre de la France," Cyrille Grand' Eury, Mem. Sav. Etrangers, xxiv. 1877.

abundant in individuals and species (C. Suckowii, Cistii, cannæformis, varians, approximatus, A. rigidus, grandis, hippuroides), Annularia radiata, Sphenophyllum. Among the ferns there are few true sphenopterids, but Neuropteris is common (N. flexuosa, auriculata), also Odontopteris (O. reichiana, Schlotheimii), Pecopteris (P. arborescens, pulchra, candolliana, villosa, oreopteridia, crenulata, aspidoides, elegans), Caulopteris, Psaronius. Lepidodendra are few (L. Sternbergii, elegans, Lepidostrobus sub-variabilis, Lepidophloios laricinus, Knorria Selloni, Lepidophyllum majus). Sigillarioid forms are likewise on the wane when compared with their profusion below (Sigillaria elliptica, Candollii, tessellata, elegans, grasiana, Brardii, spinulosa: Syringodendron cyclostigma, distans; Stigmaria ficoides abundant). Cordaites, however, now becomes the dominant group of plants, but with a somewhat different facies from that which it presents in the middle Coal-measures (C. borassifolius, C. principalis, Dadoxylon Brandlingii, Cardiocarpus emarginatus, Gutbieri, major, ovatus). Calamites cruciatus makes its appearance, also Walchia piniformis.

Middle Coal Flora—(Upper Zone, Supra-moyenne).—Calamites numerous (C. Suckowii, Cistii, cannæformis, ramosus; Asterophyllites foliosus, longifolius, grandis, rigidus; Annularia minuta, brevifolia; Sphenophyllum saxifragæfolium, Schlotheimii, truncatum, majus. Ferns represented by Sphenopteris (S. latifolia, irregularis, trifoliolata, cristata, etc.). Prepecopteris (maximum of this genus), Pecopteris (P. abbreviata, villosa, Cistii, oreopteridia, etc.), Caulopteris, Neuropteris, and other genera. Lepidodendra are not infrequent (Lepidodendron aculeatum, Sternbergii, elegans, rimosum; Lepidostrobus variabilis; Lepidophloios laricinus, Lepidophyllum majus), and various Lycopodites. The proportion of Sigillaria is always large (S. Cortei, intermedia, Sillimanni, tessellata, cyclostigma, alternans, Brongniarti, Stigmaria, ficoides, minor). Pseudosigillaria is abundant, especially P. monostigma. Cordaites appears in some places abundantly (C. borassifolius, Artisia transversa, Cladiscus schnorrianus), and its fruits are numerous and varied (Cardiocarpus emarginatus, orbicularis, ovatus).

Middle Coal Flora (properly so called), characterized above all by the dominant place of the Sigillarioids, which now surpass the lepidodendroids and form the main mass of the coal-seams. The genus Sigillaria here attains its maximum development (S. Groeseri, angusta, scutellata, intermedia, elongàta, notata, alternans, rugosa, reniformis,

leopoldina, and many more; Pseudosigillaria striata, rimosa, monostigma; Stigmaria ficoides, minor). Lepidodendroids are large and frequent (Lepidodendron aculeatum, obovatum, caudatum, rimosum, Sternbergii, elegans; Lepidophloios laricinus; Ulodendron majus, minus; Halonia tuberculata, tortuosa, regularis; Lepidophyllum majus; Lepidostrobus variabilis). The ferns are abundant and varied; the Sphenopterids include many species, of which Sphenopteris Hoeninghausii and tenella are common (also S. Bronni, Schlotheimii, tenuifolia, rigida, furcata, elegans); Alethopteris is very plentiful (A. lonchitica, Serlii, Mantelli, heterophylla); also Lonchopteris Bricii and L. Rohlii; Prepecopteris, Pecopteris, Megaphyton, Neuropteris (N. flexuosa, Loshii, tenuifolia, gigantea), Cyclopteris, Aulacopteris. The calamites are widely diffused and abundant, especially Calamites dubius, undulatus, ramosus, decoratus, Steinhaueri; Asterophyllites subhippuroides, grandis, longifolius; Volkmannia binneyana; Sphenophyllum seems here to reach its maximum, characteristic species being S. emarginatum, saxifragæfolium, erosum, dentatum, truncatum, Schlotheimii. Some coals and shales abound with Cardiocarpus, also Trigonocarpus, and Noggerathia.

Middle Coal Flora—(Lower Zone, Flore houillère sous-moyenne).—Lepidodendroids are characteristically abundant and varied (Lepidodendron aculeatum, obovatum, crenatum, Haidingeri, undulatum, longifolium; and Lepidophloios laricinus, intermedius, crassicaulis; Ulodendron, abundant in England, U. dichotomum, punctatum, majus, minus, etc.; Halonia tortuosa, regularis, etc.). Sigillarioids are numerous (Sigillaria oculata, elegans, scutellata, elongata, mamillaris, alveolaris, reniformis; Stigmaria ficoides, minor, stellata, reticulata; Dictyoxylon, Lyginodendron). Calamites abound (Calamites cannæformis, Suckowii, Cistii, decoratus, approximatus; Asterophyllites subhippuroides, longifolius; Volkmannia polystachya). Ferns likewise form a notable part of the flora, especially sphenopterids (Sphenopteris latifolia, acutifolia, elegans, dissecta, furcata, Gravenhorstii, nervosa, muricata, obtusiloba, trifoliata); also Prepecopteris silesiaca, oxyphylla, Glockeri, dentata; Megaphyton majus; Pecopteris ophiodermatica and other similar forms. The neuropterids become abundant (Neuropteris heterophylla, Loshii, gigantea, tenuifolia; Cyclopteris obliqua; Alethopteris lonchitica, etc.). The abundant Cordaites of the higher measures are absent, though the fruit Carpolithes occasionally occurs.

Infra-Coal-measure Flora—(Millstone grit, l'étage infra-houiller), characterized essentially by lepidodendroids and stigmarias.—Lepidodendron aculeatum, obovatum, crenatum, brevifolium, caudatum, carinatum, rimosum, volkmannianum; Ulodendron punctatum, ellipticum, majus; Halonia tuberculosa; Lepidophloios intermedius, laricinus. Sigillaria is not very common, but S. oculata, alveolata (Stern.), Knorrii, trigona, minima, and other species occur. The ferns are more varied than in older parts of the system, sphenopterids being the dominant types (Sphenopteris distans, elegans, tridactylites, furcata, dissecta, rigida, divaricata, linearis, acutiloba, etc.). The genus Pecopteris is represented by a few species. Neuropteris is comparatively rare (N. Loshii, tenuifolia), Alethopteris appears in the widespread species A. lonchitica, and a few others. Calamites are not relatively abundant (Calamites undulatus, Steinhaueri, communis, cannæformis, Cistii; Asterophyllites foliosus, etc.).

Flora of the Upper Graywacke.—Lepidodendroids are the prevalent forms (Lepidodendron carinatum, polyphyllum, volkmannianum, rugosum, caudatum, aculeatum, obovatum; Halonia tetrasticha, regularis; Ulodendron ovale, commutatum). Stigmaria in several species occurs, sometimes abundantly; but Sigillaria is rare (S. undulata, Voltzii, costata, subelegans, venosa, Guerangeri, verneuillana). Calamites are not infrequent (C. Roemeri, Voltzii, cannæformis, etc.). The ferns are chiefly sphenopterids (Sphenopteris dissecta, elegans, Gersdorfi, distans, tridactylites, schistorum; Cyclopteris tenuifolia, Haidingeri, flabellata; Prepecopteris aspera, subdentata; Neuropteris heterophylla, Loshii).

Flora of the Culm, characterized by the abundance of lepidodendroids of the type of L. veltheimianum (with Knorria imbricata), by the number of Bornia transitionis, associated with Calamites Roemeri, Stigmaria ficoides (and other species), and by the abundance of the palæopterid ferns (Palæopteris Machaneti, antiqua, dissecta (Sphenopteris), affinis (Fig. 364); Cardiopteris frondosa; Rhodea divaricata, elegans, moravica; Sphenopteris Göpperti, Schimperi, etc.).

Carboniferous Limestone Flora.—The palæopterid ferns reach a maximum (Palæopteris inæquilatera, lindseæformis, polymorpha, frondosa). Sphenopterid forms are found in Sphenopteris bifida, lanceolata, confertifolia. The old genus Cyclostigma here disappears (C. minuta, Nathors-

tii). The more characteristic lepidodendroids are Lepidodendron weikianum, veltheimianum, squamosum; Knorria imbricata, acicularis. The flora includes also Stigmaria ficoides, rugosa; Bornia transitionis; Asterophyllites elegans, etc.

§ 2. Local Development

The European development of the Carboniferous system presents certain well-marked local types, which bring clearly before the mind some of the successive geographical features of the time. During the earlier half of the Carboniferous period, there still lay much land toward the north and northwest of the present European area, whence a continuous supply of sandy and muddy sediment was derived. A sea of moderate depth and clear water extended from the Atlantic across the site of central Ireland, the heart of England, and Belgium into Westphalia. The southern margin of this ancient Mediterranean was probably formed by the ridge of older Palæozoic and crystalline rocks, which, extending from the west of England into the Boulonnais, and from Brittany into central France, sweeps eastward by the uplands of the Ardennes, Hundsruck, Taunus, and Thuringer Wald into Saxony and Silesia. In the deeper and clearer water, massive beds of limestone accumulated; but toward the land, at least on the north side of the sea, there was an increasingly abundant deposit of sand and mud, with occasional seams of coal and sheets of limestone. The whole region underwent slow subsidence and infilling of sediment, until at last vast marshes and jungles occupied tracts that had been previously sea. By degrees, the lower parts of the surrounding land were likewise submerged beneath the accumulating coal-growths, which consequently spread over the sinking areas. Hence, while across the central portions of the Carboniferous region the normal succession of strata presents a lower marine division, consisting mainly of limestone, and an upper brackish-water division, composed of sandstones, shales, and coal-seams, the marginal tracts show hardly any limestone, some of them indeed, as in central France, containing only the highest part of the upper division.

The British Isles.[199]—The general sequence just referred to

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[199] For detailed information regarding British Carboniferous rocks and fossils the student may consult, among early works, Phillips' "Geology of Yorkshire," 1836, and papers by Prestwich (Geol. Trans. 2d ser. v.), Sedgwick (op. cit. iv. Q. J. Geol. Soc. viii. Proc. Geol. Soc. ii.). Of later date are memoirs by Binney

is well illustrated in the structure of the Carboniferous tracts of Britain, which, being sufficiently extensive to contain more than one type of the system, cast interesting light on the varied geographical conditions under which the rocks were accumulated. As the land, whence the chief supplies of sediment were derived, rose mainly to the north and northwest, while the centre of England and Ireland lay under clear water of moderate depth, the sea shallowed northward into Scotland, and its bottom was covered with constantly accumulating banks of sand and sheets of mud. Hence vertical sections of the Carboniferous system of Britain differ greatly according to the districts in which they are taken. The subjoined table may be regarded as expressing the typical subdivisions which can be recognized, with modifications, in all parts of the country:

3. Coal-measures	Red and gray sandstones, clays and sometimes breccias, with occasional seams and streaks of coal and Spirorbis limestone: Cythere inflata, Spirorbis pusillus (carbonarius).
	Middle or chief coal-bearing series of sandstones, clays and shales, with numerous workable coals: Anthracosia, Anthracomya, Beyrichia, Estheria, Spirorbis, etc.
	Gannister beds, flagstones, shales and thin coals, with hard siliceous (gannister) pavements: Orthoceras, Goniatites, Posidonomya, Aviculopecten, Lingula, etc.
2. Millstone Grit —	Grits, flagstones and shales, with thin seams of coal.
1. Carboniferous Limestone series	Yoredale group of shales and grits, passing down into dark shales and limestones: Goniatites, Aviculopecten, Posidonomya, Lingula, Discina, etc.
	Thick (Scaur or Main) limestone in south and centre of England and Ireland, passing northward into sandstones, shales, and coals with limestones (abundant corals, polyzoa, brachiopods, lamellibranchs, etc.)
	Lower Limestone Shale of south and centre of England (marine fossils like those of overlying limestone). The Calciferous Sandstone group of Scotland (marine, estuarine, and terrestrial organisms), probably represents the Scaur Limestone and Lower Limestone Shale, and graduates downward insensibly into the Upper Old Red Sandstone.

1. CARBONIFEROUS LIMESTONE SERIES AND LOCAL EQUIVALENTS.—In the southwest of E n g l a n d, and in

(Q. J. Geol. Soc. ii. xviii.), Kirkby (op. cit. xxxvi.); Davis and Lees, "West Yorkshire," 1878; G. H. Morton, numerous papers in Proc. Liverpool Geol. Soc. Hull's "Coal-Fields of Great Britain," 4th ed. 1881. The Memoirs of the Geological Survey will be found to supply much detailed information for the various Carboniferous tracts of Britain; see, for example, the "Geology of the Yorkshire Coal-Field," by Messrs. Green and Russell, "Geology of Flint and Mold," by A. Strahan. Some local papers are referred to in subsequent notes.

South Wales, the Carboniferous system passes down conformably into the Old Red Sandstone. The passage beds consist of yellow, green, and reddish sandstones, green, gray, red, blue, and variegated marls and shales, sometimes full of terrestrial plants. They are well exposed on the Pembrokeshire coasts, marine fossils being there found even among the argillaceous beds at the top of the Red Sandstone series. They occur with a thickness of about 500 feet in the gorge of the Avon near Bristol, but show less than half that depth about the Forest of Dean. At their base there lies a bone-bed containing abundant palatal teeth. Not far above this horizon, plant-bearing strata are found. Hence these rocks bring before us a mingling of terrestrial and marine conditions. In Yorkshire, near Lowther Castle, Brough, and in Ravenstonedale, alternations of red sandstones, shales, and clays, containing Stigmaria and other plants, occur in the lower part of the Carboniferous Limestone. Along the eastern edge of the Silurian hills of the Lake district, at the base of the Pennine escarpment and round the Cheviot Hills, a succession of red and gray sandstones, and green and red shales and marls with plants, underlies the base of the Carboniferous Limestone. It is highly probable, however, that these red strata form merely a local base, and occur on many successive horizons; so that they should be regarded not as marking any particular period, but rather as indicating the recurrence or persistence of certain peculiar littoral conditions of deposit during the subsidence of the land (p. 862). Further north, in the southern counties of Scotland, the Upper Old Red Sandstone, with its characteristic fishes, graduates upward into reddish and gray sandstones with Carboniferous plants.

In Devon and Cornwall a type of the Carboniferous system is found, which, though it does not occur elsewhere in Britain, has been ascertained to reappear and to have a wide extension in central Europe. It presents a thick series of well-bedded grits, sandstones, shales, often dark gray, and occasional thin limestones, and passes down conformably into upper Devonian strata. Though much contorted and faulted, like the Devonian formations of the same region, this arenaceous and shaly series has yielded a sufficiently large number of recognizable fossils to show its geological position. The plants resemble generally those found in the Calciferous Sandstone series of Scotland. The animal remains include species of Orthoceras, Goniatites, Posidonomya (P. Becheri) Chonetes, Spirifer (S. Urei), Phillipsia,

etc., an assemblage that also points to a position low down in the Carboniferous system. This series of strata is known as the Culm-measures, and the name Culm has been adopted as the designation of this type of Lower Carboniferous rocks abroad. Bands of tuff, diabase, etc., mark contemporaneous volcanic activity during the deposition of the Devonshire Culm.[200]

In the south and southwest of England, and in South Wales, the base of the Carboniferous system consists of certain dark shales known as Lower Limestone Shale, in which a few characteristic fossils of the Carboniferous Limestone occur. These basement beds vary up to rather more than 400 feet in thickness. They are overlain conformably by the thick mass of limestone, which in Britain and Belgium forms a most characteristic member of the Carboniferous system.

The name Carboniferous Limestone (or Mountain Limestone) was given by Conybeare to the thick mass of limestone which in the southwest of England is interposed between the Old Red Sandstone and the Coal-measures. As the geological structure of the country came to be more fully known, the limestone was found to pass laterally into sandy and argillaceous strata. The term Carboniferous Limestone Series is now applied to this division of the system, which attains its greatest thickness in the north, though the limestone there forms a subordinate part of the whole series. Toward the south, on the other hand, the limestone increases in dimensions till it practically constitutes the entire thickness of the series. In the Pennine chain, which forms the axis of the north of England, the Carboniferous Limestone series attains a thickness of nearly 4000 feet, yet this is not its entire depth, for its base is not seen. Of this great thickness the lowest visible 1600 feet consist of limestone. Traced southward the limestone increases in magnitude, till in the Mendip Hills it attains its maximum thickness of about 3000 feet. Followed, on the other hand, toward the north, the calcareous part of the series diminishes to a few thin seams of limestone, the main mass of rock consisting of sandstone and shale with seams of coal and ironstone. The Pennine chain appears to have been the area of maximum depression during the early part of the Carboniferous period in England. The great and rapid vari-

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200 De la Beche, "Geology of Cornwall," etc. Ussher. Geol. Mag. 1887, p. 10, Proc. Somerset Arch. Nat. Hist. Soc. xxxviii. 1892, p. 111.

ations in thickness of the limestone may indicate inequalities in the downward movement, and perhaps to some extent irregularities in the growth of corals and the accumulation of calcareous débris. The great mass of 3000 feet of limestone in the Mendip Hills dwindles down to less than 400 feet in the Forest of Dean, a distance of only some 30 miles. The thickness rises in Monmouthshire to 1000 feet, but sinks in Glamorganshire to half that amount. Westward in Caldy Island it swells out again to 2300 feet, while still further west, on the coast of Pembrokeshire, it disappears altogether.[201]

Where typically developed, the Carboniferous Limestone is a massive well-bedded limestone, chiefly light bluish-gray in color, varying from a compact homogeneous to a distinctly crystalline texture, and rising into ranges of hills, whence its original name "Mountain Limestone." It is sometimes, especially near Bristol, distinctly oolitic, and often contains occasional scattered irregular nodules and nodular beds of dark chert (phtanite).[202] Though it is abundantly fossiliferous, little has yet been done in working out in detail the successive life-zones of this great mass of rock, as has been performed so well for the corresponding limestone series of Belgium. The fossils commonly stand out on weathered surfaces of the rock, but microscopic investigation shows that even those portions of the mass which appear most structureless consist of the crowded remains of marine organisms. The limestone has been derived entirely from the organisms of the sea-floor, either growing up into a solid mass after the manner of coral-reefs, or spreading over the bottom in sheets of crinoid detritus, or coral sand, mixed with the remains of foraminifera, mollusks, etc. Diversities of color and lithological character occur, whereby the bedding of the thick calcareous mass can be distinctly seen. Here and there, a more markedly crystalline structure has been superinduced; while along lines of

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[201] De la Beche (Mem. Geol. Surv. i. p. 112) states that the limestone is there overlapped by the Coal-measures. It would be interesting to ascertain if the disappearance of the limestone may not rather be due to an overthrust of the Coal-measures upon it. De la Beche believed that the thickest zone of the limestone lay to the south, from Mendip westward through Caldy Island, and that the thickness rapidly diminished northward.

[202] The chert bands of the Carboniferous Limestone have been shown by Dr. Hinde to be largely composed of spicules of siliceous sponges, Geol. Mag. 1887, p. 435; and "British Palæozoic Sponges," Pal. Soc. for 1887, p. 98, 1888. Dr. Hinde has also described similar beds from the Permo-Carboniferous rocks of Spitzbergen, Geol. Mag. 1888, p. 241.

principal joints the rock on either side for a breadth of 20 or 30 fathoms is occasionally converted into yellowish or brown dolomite or "dunstone" (see p. 547). In Derbyshire, sheets of contemporaneous lava, locally termed "toadstone," are interpolated in the Carboniferous Limestone. Other evidences of contemporaneous volcanic action have been noted in the Isle of Man[203] and in Devonshire,[204] but it is in Scotland, as will be immediately referred to, that the most remarkable proofs of abundantly active Carboniferous volcanoes have been preserved.

In the Carboniferous areas of the southwest of England and South Wales, the limits of the Carboniferous Limestone are well defined by the Lower Limestone Shale below, and by the Farewell Rock or Millstone Grit above. In the Pennine area, however, the massive limestone is succeeded by a series of shales, limestones, and sandstones, known as the Yoredale Group. These cover a large area and attain a great thickness. In North Staffordshire they are 2300 feet thick. In Lancashire, they attain still greater dimensions, Mr. Hull having there found them to be no less than 4500 feet thick. Both the lower or main (Scaur) limestone and the Yoredale group pass northward into sandstones and shales with coal seams. In Northumberland, the Carboniferous Limestone series has been grouped into the following subdivisions:[205]

Upper Calcareous group, from the base of the Millstone grit to the Great Limestone, 350–1200 feet.
Lower Calcareous group, from the Great Limestone to the bottom of the Dun or Redesdale Limestone, 1300–2500 feet.
Carbonaceous group, Scremerston coals, from the Dun Limestone to the top of the Fell Sandstone, 800-2500 feet.
Fell Sandstone, 500–1600 feet.
Tuedian or Cement-Stone group, 500–1500 feet.
Basement conglomerate.

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[203] J. Horne, Trans. Geol. Soc. Edin. ii. 1874, p. 332; B. Hobson, Quart. Journ. Geol. Soc. xlvii. 1891, p. 432. Yn Lioar Manninagh, Douglas, January, 1892, p. 337.

[204] De la Beche, "Report on the Geology of Cornwall," etc., 1839, p. 119; F. Rutley, "The Eruptive Rocks of Brent Tor," Mem. Geol. Surv. 1878.

[205] See G. Tate's "History of Alnwick," vol. ii. 1869, p. 441; H. Miller, Brit. Assoc. 1886, sects. p. 675; and "Geology of Otterbourne," etc., Mem. Geol. Surv. 1887.

These subdivisions are not all fully developed in any one district, but the average thickness of the whole is at least as great as in districts further south.

Traced northward into Scotland, the Carboniferous Limestone series undergoes a still further petrographical and palæontological change. Its massive limestones dwindle down, and are replaced by thick courses of yellow and white sandstone, dark shale, and seams of coal and ironstone, among which only a few thin sheets of limestone are to be met with. Scottish geologists have divided the lower half of their Carboniferous system into two well-marked series—the Calciferous Sandstones and the Carboniferous Limestone. The Calciferous Sandstone series is composed of two groups of strata—the lower of which, or Red Sandstone group, consists of red, white, and yellow sandstones, with blue, gray, green, and red marls or clays, while the upper or Cement-stone group is made up of white and yellow sandstones, blue, gray, green, and black shales and marls, thin coals, seams of limestone and cement-stone, and abundant volcanic rocks. The red sandstones pass down into the Upper Old Red Sandstone, from which they differ in the less intensity of their color, in the frequent gray and purplish tints they assume, in the absence of the deep brick-red marls so marked in the Upper Old Red Sandstone, and in the occurrence of carbonaceous streaks and tree-trunks, roots, and twigs. In the west of Scotland there occur among the red sandstones (some of which contain Upper Old Red Sandstone fishes) bands of limestone full of true Carboniferous Limestone corals and brachiopods. Hence it is evident that the Carboniferous Limestone fauna had already appeared outside the British area before the final cessation of the peculiar conditions of sedimentation of the Old Red Sandstone period. It was not, however, until these conditions had disappeared that the sea began to invade the lakes and creep over the sinking land of this part of Britain, and to bring with it the abundant Carboniferous Limestone fauna. The Calciferous Sandstones of Scotland represent a phase of sedimentation contemporaneous with the deposition of the Lower Limestone Shale and the Scaur Limestone of the Carboniferous Limestone series of England.

One of the most singular features of the Lower Carboniferous rocks of Scotland is the prodigious abundance of the intercalated volcanic rocks. So varied, indeed, are the characters of these masses, and so manifold and interesting is the light they throw upon volcanic action, that the region may

be studied as a typical one for this class of phenomena. (See Book IV. Part VII. Sect. i.) Inland sections are abundant on the sides of the hills and in the stream-courses, while along the sea-shore the rocks have been admirably exposed. Two great phases or types of volcanic action during Carboniferous time may be recognized: (1) Plateaus, where the volcanic materials were discharged so copiously that they now form broad table-lands or ranges of hills, sometimes many hundreds of square miles in extent and 1500 feet or more in thickness; (2) Puys, where the ejections were often confined to the discharge of a small amount of fragmentary materials from a single independent vent, and where, when lavas and more copious showers of ash were thrown out, they generally covered only a small area round the volcano which discharged them.[206]

The Plateau type of eruption was specially developed during the deposition of the Calciferous Sandstones. Its lavas consist of augite-olivine rocks (picrites, limburgites), basalts, porphyrites, and trachytes, while its necks or vents are filled with agglomerates, felsites, and, in East Lothian, phonolites.[207] Sheets of tuff are intercalated among the bedded lavas. The Puy type was, on the whole, of later date, reaching its chief development during the time of the Carboniferous Limestone. Its lavas are mostly basalts of various types, together with picrites, diabases, and porphyrites. Tuffs and agglomerates are abundant, not infrequently containing organic remains.

While the scattered vents of the puys, with their associated lavas and tuffs, occur on many horizons, the plateau lavas occupy a tolerably definite position in the Calciferous Sandstones, though sometimes confined to the lower part of that group, sometimes ascending to the very base of the Carboniferous Limestone series. This volcanic zone forms an important feature in the geology of southern Scotland. Composed of nearly horizontal sheets of porphyrite, diabase, and basalt, it extends from the Clyde islands on the west to Stirling on the east, and sweeps in high table-lands through Renfrewshire and Ayrshire. It reappears in East Lothian, and presents there some interesting and remarkably fresh trachytic lavas. Even far to the south, in Berwick-

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[206] Presidential Address, Quart. Journ. Geol. Soc. 1892, p. 105; Trans. Roy. Soc. Edin. xxix. p. 437.

[207] F. H. Hatch, Trans. Roy. Soc. Edin. 1892, and Presidential Address just cited.

shire, Roxburghshire, and Kirkcudbright, volcanic sheets occupy the same position, and extend across into the English border.

The upper subdivision of the Calciferous Sandstones, known as the Cement-stone group, consists of two sections differing from each other in lithological character, and pointing to distinct conditions of deposit. The lower section is made up of thin-bedded white, yellow, and green sandstones, gray, green, blue, and red clays and shales, with thin bands of pale argillaceous limestone or cement-stone. Seams of gypsum occasionally appear. These strata are, on the whole, singularly barren of organic remains. They seem to have been laid down with great slowness, and without disturbance, in inclosed basins, which were not well fitted for the support of animal life, though fragmentary plants serve to show that the adjoining slopes were covered with vegetation. They underlie the volcanic zone in Stirlingshire and the Lothians, and overlie it in Berwickshire. The upper section is chiefly developed in the basin of the Firth of Forth, where, overlying the volcanic zone, it presents an entirely distinct lithological aspect and is abundantly fossiliferous. It there usually consists of yellow, gray, and white sandstones, with blue and black shales, clay-ironstones, limestones, "cement-stones," and occasional seams of coal. The sandstones form excellent building stones, the city of Edinburgh having been built of them. Some of the shales are so bituminous as to yield, on distillation, from thirty to forty gallons of crude petroleum to the ton of shale; they have consequently been largely worked for the manufacture of mineral-oils. The limestones are usually dull gray or yellow, and close-grained, in seams seldom more than a few inches thick, and graduate by addition of clay and protoxide of iron into cement-stone; but occasionally they swell out into thick lenticular masses like the well-known limestone of Burdie House, so long noted for its remarkable fossil fishes. This limestone appears to be mainly made of the crowded cases of a small ostracod crustacean (Leperditia Okeni, var. scoto-burdigalensis). The coal-seams are few and commonly too thin to be workable, though one of them, known as the Houston coal, has been mined to some extent in Linlithgowshire. The fossils of the Cement-stone group indicate an alternation of fresh or brackish water and marine conditions. They include numerous plants, of which the most abundant are Sphenopteris affinis (Fig. 364), Lepidodendron (two or three species), Lepi-

dostrobus variabilis (Fig. 367, *b*), Araucarioxylon. Ostracod crustaceans, chiefly the Leperditia above mentioned, crowd many of the shales. With these are usually associated abundant traces of the presence of fish, either in the form of coprolites, or of scales, bones, plates, and teeth. The following are characteristic species: Elonichthys striolatus, E. Robisoni, Rhadinichthys ornatissimus, Nematoptychius Greenockii, Eurynotus crenatus (Fig. 363), Rhizodus Hibberti, Megalichthys sp., Gyracanthus tuberculatus, Callopristodus (Ctenoptychius) pectinatus. At intervals throughout the group, marine horizons occur, usually as shale bands marked by the presence of such distinctively Carboniferous Limestone species as Spirorbis carbonarius, Discina nitida, Lingula squamiformis, Bellerophon decussatus, and Orthoceras cylindraceum.[208]

The Cement-stone group of the basin of the Firth of Forth contains a great number and variety of associated volcanic masses of the puy type. At the time when it was deposited, the region of shallow lagoons, islets, and coal-growths was dotted over with innumerable small active volcanic vents. The eruptions continued into the time of the Carboniferous Limestone, but ceased before the deposition of the Millstone Grit.[209]

The Carboniferous Limestone series of Scottish geologists, probably representing the upper part of the Carboniferous Limestone series or Yoredale group of England, consists mainly of sandstones, shales, fire-clays, and coal-seams, with a few comparatively thin seams of encrinal limestone. The thickest of these limestones, known as the Hurlet or Main limestone, is usually about 6 feet in thickness, but in the north of Ayrshire swells out to 100 feet, which is the most massive bed of limestone in any part of the Scottish Carboniferous system. One of a group of limestone beds at the base of the series, it lies upon a seam of coal, and is in some places associated with pyritous shales, which have been largely worked as a source of alum. This superposition of a bed of marine limestone on a seam of coal is of

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[208] For descriptions of the Calciferous Sandstone group, see Maclaren, "Geology of Fife and the Lothians"; also the explanations to accompany the Maps of the Geological Survey of Scotland, particularly those on Sheets 14, 22, 23, 32, 33 and 34. T. Brown, Trans. Roy. Soc. Edin. xxii. 1861, p. 385; Kirkby, Q. J. Geol. Soc. xxxvi. p. 559.

[209] For an account of these Puys see Presidential Address, Quart. Journn. Geol. Soc. 1892, p. 125; Trans. Roy. Soc. Edin. xxix. p. 437. Some of the vents are represented in Figs. 297–301, 303–307 of this text-book.

frequent occurrence in Scotland. Above these lower limestones comes a thick mass of strata containing many valuable coal-seams and ironstones (Lower or Edge Coals). Some of these strata are full of terrestrial plants (Lepidodendron, Sigillaria, Stigmaria, Sphenopteris, Alethopteris); others, particularly the ironstones, and the shales associated with the limestones and ironstones, contain marine shells, such as Lingula, Discina, Leda, Myalina, Euomphalus. Numerous remains of fishes have been obtained, more especially from some of the ironstones and coals (Gyracanthus formosus and other fin-spines, Megalichthys Hibberti, Rhizodus Hibberti, with species of Elonichthys, Acanthodes, Ctenoptychius, etc.). Remains of labyrinthodonts have also been found in this group of strata, and have been detected even down in the Burdie House limestone. The highest division of the Scottish Carboniferous Limestone series consists of a group of sandstones and shales, with a few coal-seams, and three, sometimes more, bands of marine limestone. Although these limestones are each only about 2 or 3 feet thick, they have a wonderful persistence throughout the coal-fields of central Scotland. As already mentioned (p. 860), they can be traced over an area of at least 1000 square miles, and they probably extended originally over a considerably greater region. The Hurlet limestone, with its underlying coal, can also be followed across a similar extent of country. Hence it is evident that, during certain epochs of the Carboniferous period, a singular uniformity of conditions prevailed over a large region of deposit in the centre of Scotland.

A distinguishing feature of the Carboniferous Limestone series of Scotland is the abundance of its intercalated volcanic rocks of the puy type. They are well developed in the basin of the Forth and in North Ayrshire. The lavas and tuffs are interbedded among the ordinary sedimentary strata, and the tuffs are sometimes full of plants or of marine shells, crinoids, etc.[210]

The difference between the lithological characters of the Carboniferous Limestone series, in its typical development as a great marine formation, and in its arenaceous and argillaceous prolongation into the north of England and Scotland, has long been a familiar example of the nature and application of the evidence furnished by strata as to former

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[210] See the papers cited already, p. 1371.

geographical conditions. It shows that the deeper and clearer water of the Carboniferous sea spread over the site of Yorkshire, Derbyshire, and Lancashire; that land lay to the north, and that, while the whole area was undergoing subsidence, the maximum movement took place over the area of deeper water. The sediment derived from the north, during the time of the Carboniferous Limestone, seems to have sunk to the bottom before it could reach the great basin in which foraminifers, corals, crinoids, and mollusks were building up the thick calcareous deposit. Yet the thin limestone bands, which run so persistently among the Lower Carboniferous rocks in Scotland, prove that there were occasional episodes during which sediment ceased to arrive, and when the same species of shells, corals, and crinoids spread northward toward the land, forming for a time, over the sea-bottom, a continuous sheet of calcareous ooze, like that of the deeper water further south. These intervals of limestone-growth no doubt point to times of more rapid submergence, perhaps also to other geographical changes, whereby the sediment was for a time prevented from spreading so far. It is further deserving of remark that the fossils in these thin upper limestones in Scotland, though specifically identical with those in the thick lower limestones and in the massive Carboniferous Limestone of central and southwestern England, are often dwarfed forms, as if the conditions of life were much less favorable than where the thicker sheets of calcareous material were accumulated. The corals, for instance, are generally few in number and small in size, and the large Productus (P. giganteus) is reduced to a half or third of the dimensions it attains in its best development.

Viewed as a whole, the Carboniferous Limestone series of the northern part of the British area contains the records of a long-continued but intermittent process of subsidence. The numerous coal-seams, with their under-clays, may be regarded as surfaces of vegetation that grew in luxuriance on wide marine mud-flats. They mark pauses in the subsidence. Perhaps we may infer the relative length of these pauses from the comparative thicknesses of the coal-seams. The overlying and intervening sandstones and shales indicate a renewal of the downward movement, and the gradual infilling of the depressed area with sediment, until the water once more shoaled, and the vegetation from adjacent swamps spread over the muddy flats as before. The occasional limestones serve to mark epochs of more prolonged or more rapid subsidence, when marine life was enabled to flourish over the

site of the submerged forests. But that the sea, even though tenanted in these northern parts by a limestone-making fauna, was not so clear and well suited for the development of animal life during some of these submergences as it was further south, seems to be proved by the paucity and dwarfed forms of the fossils, as well as by the admixture of clay in the stone.

Ireland presents a development of Carboniferous rocks which on the whole follows tolerably closely that of the sister island. In the northern counties, the lowest members are evidently a prolongation of the type of the Scottish Calciferous Sandstones. In the southern districts, however, a very distinct and peculiar facies of Lower Carboniferous rocks is to be observed. Between the Old Red Sandstone and the Carboniferous Limestone there occurs in the county of Cork an enormous mass (fully 5000 feet) of black and dark-gray shales, impure limestones, and gray and green grits, which have been so affected by slaty cleavage as to have assumed more or less perfectly the structure of true cleaved slates. To these rocks the name of Carboniferous Slate was given by Griffith. They contain numerous Carboniferous Limestone species of brachiopods, echinoderms, etc., as well as traces of land-plants in the grit bands. Great though their thickness is in Cork, they rapidly change their lithological character and diminish in mass, as they are traced away from that district. In the almost incredibly short space of 15 miles, the whole of the 5000 feet of Carboniferous Slate of Bantry Bay seems to have disappeared, and at Kenmare the Old Red Sandstone is followed immediately and conformably by the Limestone with its underlying shale. This rapid change is probably to be explained, as Jukes suggested, by a lateral passage of the slate into limestone; the Carboniferous Slate being, in part at least, the equivalent of the Carboniferous Limestone. Between Bandon and Cork the Carboniferous Slate is conformably overlain by dark shales containing Coal-measure-fossils, and believed to be true Coal-measures. Hence in the south of Ireland, the thick calcareous accumulations of the limestone series appear to be replaced by a corresponding depth of argillaceous sedimentary rocks.[211]

The Carboniferous Limestone swells out to a great thickness, and covers a large part of Ireland. It attains a maximum in the west and southwest, where, according to Mr.

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[211] J. B. Jukes, Memoirs Geol. Survey, Ireland. Explanation of Sheets 194, 201 and 202, p. 18; Explanation of Sheets 187, 195 and 196, p. 35.

Kinahan,[212] it consists in Limerick of the following subdivisions:

Upper (Burren) Limestone	Bedded limestone	240 ft.
	Cherty zone	20
Upper (Calp) Limestone	Limestones and shales	1000
	Cherty zone	40
Lower Limestone	Fenestella limestone	1900
	Lower cherty zone	20
	Lower shaly limestones	280
Lower Limestone Shales		100
		3600

The chert (phtanite) bands which form such marked horizons among these limestones are counterparts of others found abundantly in the Carboniferous Limestone of England and Scotland. Portions of the limestone have a dolomitic character, and sometimes are oolitic. Great sheets of porphyrite, basalt, and tuff, representing volcanic eruptions of contemporaneous date, are interpolated in the Carboniferous Limestone of Limerick.[213] As the limestone is traced northward, it shows a similar change to that which takes place in the north of England, becoming more and more split up with sandstone, shale, and coal-seams.[214]

2. MILLSTONE GRIT.—This name is given to a group of sandstones and grits, with shales and clays, which runs persistently through the centre of the Carboniferous system from South Wales into the middle of Scotland. In South Wales, it has a depth of 400 to 1000 feet; in the Bristol coal-field, of about 1200 feet. Traced northward it is found to be intercalated with shales, fire-clays, and thin coals, and, like the lower members of the Carboniferous system, to swell out to enormous dimensions in the Pennine region. In North Staffordshire, according to Mr. Hull, it attains a thickness of 4000 feet, which in Lancashire increases to 5500 feet. These massive accumulations of sediment were deposited on the north side of a barrier of more ancient Palæozoic rocks, which, during all the earlier part of the Carboniferous period, seems to have extended across central England, and which was not submerged until part of the Coal-measures had been laid down. North of the area of maximum deposit, the Millstone Grit thins away to not more than 400 or 500 feet. It continues a comparatively insignificant formation in Scotland, attaining its greatest thickness in Lanarkshire

212 "Geology of Ireland," p. 72.
213 Presidential Address, Quart. Journ. Geol. Soc. 1892, p. 145
214 Hull's "Physical Geology and Geography of Ireland," 2d edit. 1891, p. 49.

and Stirlingshire, where it is known as the "Moor Rock." In Ayrshire it does not exist, unless its place be represented by a few beds of sandstone at the base of the Coal-measures.

The Millstone Grit is generally barren of fossils. When they occur, they are either plants, like those in the coal-bearing strata above and below, or marine organisms of Carboniferous Limestone species. In Lancashire and South Yorkshire, indeed, it contains a band of fossiliferous calcareous shale indistinguishable from some of those in the Yoredale group and Scaur limestone.

3. COAL-MEASURES.—This division of the Carboniferous system consists of numerous alternations of gray, white, yellow, sometimes reddish, sandstone, dark-gray and black shales, clay-ironstones, fire-clays, and coal-seams. In South Wales it attains a maximum depth of about 12,000 feet; in the Bristol coal-field, about 6000 feet. But in these districts, as in most of the Carboniferous areas of Britain, we cannot be sure that all the Coal-measures originally deposited now remain, for they are generally unconformably covered by later formations. Palæontological considerations, to be immediately adverted to, render it probable that the closing part of the Carboniferous period is not now represented in Britain by fossiliferous strata. Toward the end of the Carboniferous period, possibly also within early Permian time, the Carboniferous strata were in many if not most districts of Britain upheaved so as to be exposed to denudation. In some areas the denudation was so great that the Permian rocks, as in the case of the Magnesian Limestone of Durham, sweep across the denuded edges of the Coal-measures, Millstone grit, and even the higher parts of the Carboniferous Limestone. But these disturbances and erosion were not universal within the British region, for we find that over parts of South Staffordshire these strata are followed with apparent conformability by the Permian sandstones. In North Staffordshire, the depth of Coal-measures is about 5000 feet, which in South Lancashire increases to 8000. These great masses of strata diminish as we trace them eastward and northward. In Derbyshire, they are about 2500 feet thick, in Northumberland and Durham about 2000 feet, and about the same thickness in the Whitehaven coal-field. In Scotland, they attain a maximum of over 2000 feet.

The Coal-measures are susceptible of local subdivisions indicative of different and variable conditions of deposit. The following table shows the more important of these:

Glamorganshire	Feet.	South Lancashire	Feet.	Central Scotland	Feet.
Upper series: sandstones, shales, etc., with 26 coal-seams, more than . .	3400	Upper series: shales, red sandstones, Spirorbis limestone, ironstone and thin coal-seams .	1600 to 2000	Upper red sandstones and clays, with Spirorbis limestone; in Fife upward of .	900
Pennant Grit: hard, thick-bedded sandstones, and 15 coal-seams	3246	Middle series: sandstones, shales, clays, and thick coal-seams The chief repository of Coal .	3000 to 4000	True coal-measures: sandstones, shales, fire-clays, with bands of black-band ironstone, and numerous seams of coal. Thickness in Lanarkshire upward of . . .	2000
Lower series: shales, ironstones, and 34 coal-seams .	450 to 850	Lower or Gannister series: flagstones, shales, and thin coals . .	1400 to 2000		
Millstone Grit.		Millstone Grit.		Moor Rock, or Millstone Grit.	

The numerous beds of compressed vegetation form the most remarkable feature of the Coal-measures. As already stated, coal-seams in Britain are usually underlain by fire-clay (*mur* of the Belgian coal-fields), which, traversed in all directions by rootlets, and free, or nearly free of alkalies and iron, appears to have been the soil on which the plants that formed the coal grew. A coal-seam accordingly marks there a former surface of terrestrial vegetation, and the shales, fissile micaceous sandstones, and other strata that overlie it show the nature of the sediment under which it was eventually buried.

The Coal-measures of Britain have not yet been very precisely subdivided into palæontological zones. The lower portions or Gannister beds of Lancashire contain at least 70 species of undoubtedly marine fossils, including species of Goniatites (G. Listeri), Orthoceras, Nautilus, Edmondia, Posidonia, Sanguinolites, Aviculopecten (A. papyraceus), Lingula (L. squamiformis), Discina, Productus, Spirifer, etc. Other horizons with marine fossils have been observed in England and Scotland even in the upper Coal-measures.[215] The middle and upper divisions are characterized by the prevalence of species of Anthracosia, Anthracoptera, and Anthracomya. These shells are not met with in association with the more typical marine fauna, but, on the contrary, are mingled with a peculiar assemblage of fishes and reptiles, annelids and crustaceans, such as might be supposed to inhabit brackish or fresh water, together

[215] J. W. Kirkby, Quart. Journ. Geol. Soc. xliv. 1888, p. 747.

with abundant remains of terrestrial vegetation.[216] Some of the more characteristic fishes are Strepsodus sauroides (Fig. 372), Rhizodopsis sauroides, Megalichthys Hibberti, Cheirodus granulosus (Fig. 372), Janassa linguiformis, Sphenacanthus hybodoides (Fig. 361), Pleuracanthus lævissimus, Ctenoptychius apicalis. Some species range from bottom to top of the Coal-measures; *e.g.* Callopristodus (Ctenoptychius) pectinatus and Gyracanthus formosus.[217]

Little has yet been done in working out the stratigraphical distribution of the Coal-measure flora of Britain, but some recent progress in this direction has been made by Mr. Kidston, who believes the Coal-measures to be divisible into Upper (Radstock, Somerset), Middle (South Staffordshire, part of Yorkshire), and Lower (part of Yorkshire, Northumberland, Scotland).[218] The late D. Stur, correlating the Coal-measures of this country with those of central Europe mainly by means of the plants, regarded the Coal-measures of Wales and the west of England generally as equivalent to the higher series of Germany, those of central and northern England and Scotland as equivalent to the lower series, both of these series being represented in Lancashire.[219] From plant-remains obtained recently from the chalk at Dover, Zeiller regards the Coal-measures there as belonging to the upper part of the middle Coal-measures of France.[220]

On the continent of Europe the Carboniferous system occupies many detached areas or basins—the result partly of original deposition, partly of denudation, and partly of the spread and overlap of more recent formations. There can be no doubt that the English Carboniferous Limestone once extended continuously eastward across the north of France, along the base of the Ardennes, through Belgium, and across the present valley of the Rhine into Westphalia. From the western headlands of Ireland this calcareous formation can thus be traced eastward for a distance of 750 English miles into the heart of Europe. It then begins to pass

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216 Wheelton Hind, Quart. Journ. Geol. Soc. xlix. 1893, p. 259.

217 My friend Dr. Traquair has been kind enough to furnish me with information on this subject, which he has so carefully studied.

218 Trans. Roy. Soc. Edin. xxxv. 1890–91, pp. 63, 391; xxxvii. 1893, p. 307.

219 Jahrb. k. k. Geol. Reichsanst. 1889.

220 Compt. Rend. Oct. 24, 1892. The details of this Dover boring, which has proved the existence of coal-bearing strata beneath the southeast of England, are given by Lorieux, Ann. Mines, ser. 9, vol. ii. 1892, p. 227. Bertrand has discussed the relations of this Dover coal-field to those of northern France and Belgium, op. cit. iii. 1893, p. 1.

into a series of shales and sandstones, which, as already remarked, represent proximity to shore, like the similar strata in the north of England and Scotland. In Silesia, and still much further eastward, in central and southern Russia, representatives of the Carboniferous Limestone or Culm appear, but interstratified, as in Scotland, with coal-bearing strata. Traces of the same blending of marine and terrestrial conditions are found also in the north of Spain. But over central France, and eastward through Bohemia and Moravia into the region of the Carpathians, the Coal-measures rest directly upon older Palæozoic groups, most commonly upon gneiss and other crystalline rocks. These tracts had no doubt remained above water during the time of the Carboniferous Limestone, but were gradually depressed during that of the Coal-measures.

France and Belgium.—In Belgium and the north of France the British type of the Carboniferous system is well developed.[221] It comprises the following subdivisions:

Coal-measures—Systeme (Étage) Houiller.

- Zone of the gas-coals (Charbons à gaz, rich bituminous coals, with 28 to 40 per cent of volatile matter), containing 47 seams of coal. Pecopteris nervosa, P. dentata, P. abbreviata, Alethopteris Serlii, Neuropteris heterophylla, Sphenopteris irregularis, S. macilenta, S. coralloides, S. herbacea, S. furcata, Calamites Suckowii, Annularia radiata, Sphenophyllum erosum, Sigillaria tesselata, S. mamillaris, S. rimosa, S. laticosta, Dorycordaites.
- Zone of the "Charbons gras" (18 to 28 per cent volatile matter), soft caking coal (21 seams), well suited for making coke. Sphenopteris nummularia, S. macilenta, S. chærophylloides, S. artemisifolia, S. herbacea, S. irregularis, Neuropteris gigantea, Alethopteris Serlii, A. valida, Calamites Suckowii, Sphenophyllum emarginatum, Sigillaria polyploca, S. rimosa, S. laticosta, Trigonocarpus Nöggerathii.
- Zone of the "Charbons demi-gras" (12 to 18 per cent volatile matter), 29 seams of coal, chiefly fitted for smithy and iron-work purposes. Sphenopteris convexifolia, S. Hœninghausi, S. trichomanoides, S. furcata, S. Schillingsii, S. irregularis, Lonchopteris rugosa, Calamites Suckowii, Annularia radiata, Sigillaria mamillaris, S. elegans, S. piriformis, S. elliptica, S. scutellata, S. Groeseri, S. lævigata, S. rugosa, Halonia tortuosa.
- Zone of the "Charbons maigres." Lean or poor coals (20 to 25 seams), only fit for making bricks or burning lime (9 to 12 per cent volatile matter). Pecopteris Loshii, P. pennæformis, Neuropteris heterophylla, Alethopteris lonchitica, Sphenophyllum saxifragæfolium, Annularia radiata, Sigillaria conferta, S. Candolli, S. Voltzii, Calamites Suckowii, Lepidodendron rhodeanum, L. pustulatum, Lepidophloios laricinus.

[221] On the Carboniferous rocks of this area see De Koninck, "Descriptions des Animaux Fossiles du Terrain Carbonifere de la Belgique," 1842–67. Gosselet's "Esquisse," already cited, and his "L'Ardenne," 1888, chaps. xxii. and xxiii. Mourlon's "Geologie." Boulay, "Terrain Houiller du Nord de la France et ses Vegetaux fossiles," Lille, 1876. Dupont, Bull. Soc. Roy. Belg. 1883.

Coal, etc.	Zone of Productus carbonarius. Goniatites diadema, G. atratus, Spirifer mesogonius, S. glaber, S. trigonalis, Streptorhynchus crenistria, Productus semi-reticulatus, P. marginalis, Avicula papyracea, Schizodus sulcatus.
Millstone Grit.	Sandstones or quartzites passing into conglomerates, separated from the Carboniferous Limestone below by carbonaceous shales with some thin coal-seams; chiefly developed toward the northeast (Liege, Aix-la-Chapelle).

		Thickness in metres in area of the Sambre	Thickness in metres in area of the Meuse
Carboniferous Limestone—Calcaire Carbonifere, Système Calcareux.	Limestone of Visé. Often poor in fossils, distinguished by Productus giganteus	50	250
	Limestone of Limont (Napoleon marble of Boulonnais). Fossils numerous: Productus undatus, P. semireticulatus, Spirifer glaber, S. duplicicostus, Rhynchonella pleurodon, Terebratula sacculus	10	
	Limestone of Haut Banc, compact or oolitic in south part of Sambre basin, with Productus sublævis; but in north part of that basin, as well as on the Meuse and in the Boulonnais, Productus cora replaces P. sublævis	40	150
	Dolomite of Namur, well developed between Namur and Liège, and extending into the Boulonnais (Hure dolomite), alternating with gray limestone, containing Chonetes comoides	40	
	Limestone of Bachant, gray, bluish-black, or black, with cherts (phtanites). Productus cora (and sometimes P. giganteus), Spirifer tricornis, Dentalium priscum, Euomphalus cirroides, Nautilus sulcatus, Orthoceras munsterianum	35	100
	Limestone of Waulsort, gray, often dolomitic; only seen in area of the Meuse. Spirifer cuspidatus, Conocardium aliforme	0	100
	Limestone of Anseremme, gray and blue-veined limestone and dolomite. Productus semireticulatus, Spirifer mosquensis, S. cuspidatus, Orthis resupinata .	8	60
	Limestone of Dinant, only found in the Meuse area. Productus semireticulatus, P. Flemingii, Pecten intermedius	0	100
	Limestone of Ecaussines ("petit granite"), crinoidal limestone. Phillipsia gemmulifera, Productus semireticulatus, Spirifer mosquensis, Streptorhynchus crenistria, Orthis Michelini, Strophomena rhomboidalis.	25	
	Limestones and shales of Avesnelles, black limestone, 16 metres, resting upon argillaceous shales, 40 metres. Among the numerous fossils of the limestone are Productus Flemingii, P. Héberti, Chonetes variolaris, Rhynchonella pleurodon, Spirifer mosquensis, Euomphalus equalis, Pecten Sowerbyi	50	
		258	760

The base of these strata passes down conformably into the Devonian system, with which, alike by palæontological and petrographical characters, it is closely linked. The Carboniferous rocks of the north of France and of Belgium have undergone considerable disturbance. A remarkable fault ("la grande faille" of this region) resulting from the rupture of an isoclinal syncline, and the consequent sliding of the inverted side over higher beds, runs from near Liège westward into the Boulonnais, with a general but variable hade toward the south. On the southern side lie lower Devonian strata, below which the Carboniferous Limestone and even Coal-measures are made to plunge. Bores and pits near Liège at the one end, and in the Boulonnais[222] at the other, have reached workable coal, after piercing the inverted Devonian rocks. By continuing the boring the same coals are found at lower levels in their normal positions. Besides this dominant dislocation many minor faults and plications have taken place in the Carboniferous area, some of the coal-seams being folded zig-zag, so that at Mons a bed may be perforated six times in succession by the same vertical shaft, in a depth of 350 yards. At Charleroi a series of strata, which in their original horizontal position occupied a breadth of $8\frac{1}{2}$ miles, have been compressed into rather less than half that space by being plicated into twenty-two zig-zag folds.

Southward the plateau of crystalline rocks in central France is dotted with more than 300 small Carboniferous basins which contain only portions of the Coal-measures. The most important of these basins are those of the Roannais and Beaujolais, St. Etienne, Autun, Commentry, Gard, and Brive. It would appear, however, that some of the surrounding slates are altered representatives of the lower parts of the Carboniferous system, for Carboniferous Limestone fossils have been found in them between Roanne and Lyons, and near Vichy.[223] Even as far south as Montpellier, beds of limestone full of Productus giganteus and other charac-

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[222] For the Boulonnais, see Godwin-Austen, Q. J. Geol. Soc. ix. p. 231; xii. p. 33; Barrois, Proc. Geol. Assoc. vi. No. 1; Report of meeting at Boulogne, Bull. Soc. Geol. France, ser. 3, viii. p. 483; Rigaux, Mem. Soc. Sci. Boulogne, vol. xiv. 1892; "Notice Geol. sur le Bas Boulonnais," Boulogne-sur-mer 1892.

[223] Murchison, Q. J. Geol. Soc. vii. 1851, p. 13; Julien, Comptes Rendus, lxxviii. p. 74.

teristic fossils are covered by a series of workable coals. Grand' Eury, from a consideration of the fossils, regards the coal-basins of the Roannais and lower part of the basin of the Loire, as belonging to the age of the "culm and upper graywacke," or of strata immediately underlying the true Coal-measures. But the numerous isolated coal-basins of the centre and south of France he refers to a much later age. He looks on these as containing the most complete development of the upper coal, properly so-called, inclosing a remarkably rich, and still little-known, flora, which serves to fill up the palæontological gap between the Carboniferous and Permian periods.[224] Some of these small isolated coal-basins are remarkable for the extraordinary thickness of their coal-seams. In the most important of their number, that of St. Etienne, from 15 to 18 beds of coal occur, with a united thickness of 112 feet, in a total depth of 2500 feet of strata. In the basin near Chalons and Autun the main coal averages 40, but occasionally swells out to 130 feet, and the Coal-measures are covered, apparently conformably, by Permian rocks, from which a remarkable series of saurian remains has been obtained. Other Carboniferous areas appear in the northwest of France, where representatives of the Carboniferous Limestone and the coal-bearing series above it are found. The Carboniferous Limestone is also well developed westward in the Cantabrian mountains in the north of Spain, where it likewise is surmounted by coal-bearing strata.[225]

Germany.[226]—The Coal-measures extend in detached basins northeastward from central France into Germany. One of the most important of these, the basin of Pfalz-Saarbücken, lying unconformably on Devonian rocks, contains a mass of Coal-measures believed to reach a maximum thickness of not less than 20,000 feet, and divided into two groups:

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[224] Grand' Eury, "Flore Carbonifere." Bertrand, Bull. Soc. Geol. France, xvi. 1888, p. 517; Fayol, p. 968 *et seq.*, Memoirs cited ante, p. 1340; G. Mouret, "Bassin Houiller de Brive," 1891.

[225] The coal-field of the Asturias is described by Barrois, "Recherches sur les Terrains anciens des Asturies," p. 551. Zeiller, Mem. Soc. Geol. Nord, i. 1882, refers the plants to the Middle and Upper Coal-measures of France.

[226] Geinitz, "Die Steinkohlen Deutschlands," Munich, 1865; Von Dechen, "Erläuterungen zur Geol. Karte der Rheinprov." ii. 1884; C. E. Weiss, "Fossile Flora der jüngsten Steinkohlenformation und des Rothliegenden im Saar-Rhein Gebiete," 1869–72.

2. Upper or Ottweiler beds, from 6500 to 11,700 feet thick, consisting of red sandstones at the top, and of sandstones and shales, containing 20 feet of coal in various seams. Pecopteris arborescens, Odontopteris obtusa, Anthracosia, Estheria, Leaia; fish-remains.
1. Lower or main coal-bearing (Saarbrücken) beds, 5200 to 9000 feet thick, with 82 workable and 142 unworkable coal-seams, or in all between 350 and 400 feet of coal. Abundant plants of the middle and lower zone of the upper coal flora.

The Franco-Belgian Coal-field is prolonged across the Rhine into Westphalia. The Carboniferous Limestone here dwindles down as a calcareous formation, and assumes the "Culm" phase, passing up into the "flotzleerer Sandstein" or Millstone Grit — a group of sandstones, shales, and pebbly beds some 3000 feet thick, but without coal-seams. These barren measures are succeeded by the true Coal-measures about 10,000 feet thick, with 90 workable seams of coal, having a united thickness of more than 250 feet.

Southern Germany, Bohemia.—Carboniferous rocks occur in many scattered areas across Germany southward to the Alps and eastward into Silesia, including representatives both of the lower or Culm phase and of the Coal-measures. The Culm rocks reappear in the Harz, where they are traversed by metalliferous veins and inclose small patches of Coal-measures. The same structure extends into Thuringia, the Fichtelgebirge, Saxony, and Bohemia, the Culm yielding Carboniferous Limestone fossils, as well as Lepidodendron, etc., and containing sometimes, as in Saxony, workable coals. This union of fossils characterizes the series of shales, sandstones, graywackes, and conglomerates which forms the German Culm. The abundant fauna of the Carboniferous Limestone is reduced to a few mollusks (Productus antiquus, P. latissimus, P. semireticulatus, Posidonomya Becheri, Goniatites sphæricus, Orthoceras striatulum, etc.). The Posidonomya particularly characterizes certain dark shales known as "Posidonia schists." Of the plants, typical species are Calamites transitionis, Lepidodendron veltheimianum, Stigmaria ficoides, Sphenopteris distans, Cyclopteris tenuifolia. This flora bears a strong resemblance to

that of the Calciferous Sandstones of Scotland. True Coal-measures, however, also occur in these regions, though to a smaller extent than the lower parts of the system. One of the most extensive coal-fields is that of Silesia,[227] where the seams of coal are both numerous and valuable, one of them attaining a thickness of 50 feet. It is noteworthy that in the Coal-measures of eastern and southern Germany horizons of marine fossils occur like those so marked in the corresponding strata of Britain.

The coal-field of Pilsen in Bohemia occupies about 300 square miles. It consists mainly of sandstone, passing sometimes into conglomerate, and interstratified with shales and a few seams of coal which do not exceed a total thickness of 20 feet of coal. In its upper part is an important seam of shaly gas-coal (Plattel, or Brettelkohle), which, besides being valuable for economic purposes, has a high palæontological interest from Dr. Fritsch's discovery in it of a rich fauna of amphibians and fishes. The plants above and below this seam are ordinary typical Coal-measure forms,[228] but these animal remains present such close affinities to Permian types, that the strata containing them may belong to the Permian system (pp. 1400, 1408). What are believed to be true Permian rocks in the Pilsen district seem to overlie the coals unconformably.

Alps, Italy.—The Carboniferous strata of the Alps have been already (p. 1032) referred to in connection with the metamorphism of that region. In the western part of the chain they occur imbedded in or associated with a great series of reddish sandstones, conglomerates and red-greenish shales or slates, which occasionally become quite crystalline, and cannot indeed be satisfactorily separated from what have been regarded as the primitive schists of the mountains. To these strata the name of "Verrucano" has been given. That they are partly, at least, of Carboniferous age is shown by the characteristic flora, amounting to upward of 60 species, which the dark carbonaceous bands have yielded.[229]

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[227] D. Stur, Abhandl. k. k. Geol. Reichsanst. 1877.

[228] From the coal-field of central Bohemia C. Feistmantel enumerated 278 species of plants, of which 137 were ferns: Sphenopteris, Neuropteris, Odontopteris, Cyatheites, Alethopteris, Megaphyton, etc. Archiv. Naturw. Landes durchforsch. Böhmen, v. No. 3, 1883. For the amphibian remains, see Fritsch's "Fauna der Gaskohle."

[229] For an essay on these rocks, see L. Milch's "Beiträge zur Kenntniss der

In Italy the Carboniferous and Permian rocks are so closely related and so similar that it is doubtful to which system some of the intermediate portions should be assigned. At Monte Pizzul in the Carnic Alps, the lower strata contain Productus giganteus and P. semireticulatus, while the highest are characterized by numerous forms of Fusulina, Fenestella, etc.[230] In other parts of the same region lower strata of the age of the Culm of Germany have been described by Stur and Stache.

Russia.—Over a vast region of the east of Europe Carboniferous limestones, sandstones, shales, and thin coal-seams are spread out almost horizontally. They unite the marine and terrestrial types of sedimentation so characteristic of the north of Britain. In the central provinces of Russia, the Moscow basin or coal-field of Tula, said to occupy an area of 13,000 square miles, lies conformably on the Old Red Sandstone or Devonian system, and contains limestones full of Carboniferous Limestone fossils, and a few poor seams of coal. In the south of the empire, the coal-field of the Donetz, covering an area of 11,000 square miles, contains 60 seams of coal, of which 44, having a united thickness of 114 feet, are workable. Again, on the flanks of the Ural Mountains, the Carboniferous Limestone series has been upturned and contains some workable coal-seams. It would appear, therefore, that this particular type of mingled marine and terrestrial strata of Carboniferous age, occupies a vast expanse under later formations in the east of Europe. Since so much of the Russian development of the Carboniferous system consists of limestone, it is interesting to find that it contains many of the familiar fossil species of the Carboniferous Limestone of Western Europe. Thus in the Ural region, according to Prof. Tschernyschew, the Carboniferous system may be divided into five zones, of which the lowest, a limestone containing Productus giganteus, P. striatus, Chonetes papilionacea, etc., and the next a limestone with Spirifer mosquensis, may be regarded as corresponding to the typical Carboniferous Limestone of the west. The three upper zones, viz. those of (*a*) Syringopora parallela, Spirifer

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Verrucano," Leipzig, 1892. The metamorphism of Carboniferous and Permian rocks in the Alps of Savoy is described by P. Ternier, Bull. Carte Geol. France, ii. 1891, p. 367.

[230] A. Tommasi, Boll. Soc. Geol. Ital. viii. p. 564; C. F. Parona and L. Bozzi, op. cit. ix. pp. 56, 71.

striatus, etc., (*b*) Productus cora, and (*c*) Spirifer fasciger and Conocardium uralicum, are probably equivalent to the Millstone Grit and Coal-measures.[231] One of the most abundant and persistent organisms of the upper zones is the foraminifer Fusulina. The upper Carboniferous rocks on the west side of the Urals shade upward into the base of the Permian system, and show a commingling of Carboniferous and Permian fossils.

Even as far north as **Spitzbergen** a characteristic Carboniferous flora has been obtained, comprising 26 species of plants, half of which are new, but among which we recognize such common forms as Lepidodendron Sternbergii and Cordaites borassifolius.[232]

Africa.—The sea in which the brachiopods, corals, and crinoids of the Carboniferous Limestone lived extended across the Mediterranean basin into Africa. Species of Productus, Athyris, Spirifer, Streptorhynchus, Orthis, Cyathophyllum, etc., have been obtained in the western Sahara between Morocco and Timbuctoo.[233] The red sandstones, which extend into the peninsula of Sinai and thence into Palestine, have yielded stems of Lepidodendron and Sigillaria, and an intercalated limestone contains Orthis Michelini and Streptorhynchus crenistria.[234] A number of characteristic brachiopods of the Carboniferous Limestone have also been obtained from the hills in the Egyptian desert to the west of the Gulf of Suez, such as Rhynchonella pleurodon, Productus semireticulatus, Spirifer striatus.[235] In Southern Africa the existence of Carboniferous rocks has long been known. Above certain slates and sandstones (Bokkeveldt) containing fossils with Devonian affinities come the quartzites of Cape Colony, inclosing Lepidodendron and other Carboniferous plants. These are unconformably overlain by the "Dwyka Conglomerate," probably in great part of volcanic origin, and the Ecca mudstones and sandstones, some 4000 feet thick. After another great unconformability come the Kimberley shales and the "Karoo Beds," which

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[231] Ann. Soc. Geol. Nord, xvii. 1890, p. 201. Nikitin, Mem. Com. Geol. Russ. v. 1890, No. 5.

[232] Heer, Flora Fossilis Arctica, iv. 1877, p. 4.

[233] G. Stache, Denksch. Acad. Wiss. Wien, xlvi. 1893.

[234] R. Tate, Quart. Journ. Geol. Soc. xxvii. 1871, p. 404.

[235] J. Walther, Zeitsch. Deutsch. Geol. Ges. 1890, p. 419.

have been compared with the Permian and Trias rocks of Europe.[236]

Asia.—The Carboniferous system is extensively developed in Asia. In China, where it covers an area of many thousand miles, forming a succession of vast tablelands, it has been found by Richthofen to be composed of three stages: 1st, a massive brown bituminous limestone, which from its foraminifera (Fusulina, Susulinella, Lingulina, Endothyra, Valvulina, Climacammina) is obviously the equivalent of the Carboniferous Limestone of Europe. It is covered by (2d) productive Coal-measures with both bituminous and anthracitic coals, and containing a characteristic Coal-measure flora, among which are numerous ferns of the genera Sphenopteris, Palæopteris, Cyclopteris, Neuropteris, Callipteridium, Cyatheites, etc., also species of Calamites, Sphenophyllum, Lepidodendron (including L. Sternbergii), Stigmaria (S. ficoides), Cordaites, and others. 3d, Upper Carboniferous—sandstones, conglomerates and thin limestones, containing marine fossils, among which are the cosmopolitan brachiopods mentioned on p. 1344.[237]

Australasia.—In Australia, important tracts of true Carboniferous rocks, with coal-seams, range down the eastern colonies, and are specially developed in New South Wales, where they are divisible into: 1st, Lower Carboniferous—sandstones, conglomerates, limestones, shales, much disturbed in some places, traversed by valuable auriferous quartz-reefs, and yielding abundant plant-remains (Lepidodendron veltheimianum, L. nothum, species of Bornia, Sphenopteris, Calamites, Rhacopteris, etc.). 2d, Upper or Permo-Carboniferous, including a series of coal-bearing strata, both below and above which are thick masses of calcareous conglomerates and sandstone abounding in marine fossils. The coal-seams are sometimes 30 feet thick, and among the plants associated with them are five species of Glossopteris, also species of Phyllotheca, Annularia, and Noggerathiopsis. The genus Glossopteris was formerly believed to be entirely Mesozoic, and its occurrence with true Carboniferous organisms was for a time denied. There can now be no doubt, however, that it appears among strata in which

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236 A. H. Green, Quart. Journ. Geol. Soc. xliv. 1888, p. 240.
237 Richthofen, "China," vols. ii. and iv.

are found the widespread and characteristic **Carboniferous** Limestone forms **Lithostrotion basaltiforme, L. irregulare,** Fenestella plebeia, **Athyris Royssii,** Orthis **Michelini, O.** resupinata, **Productus aculeatus, P. cora, P.** longispinus, P. punctatus, P. semireticulatus, and many more.[238] Prof. T. W. E. David, in summarizing our knowledge of the coal-bearing rocks of New South Wales, gives a thickness of 11,150 feet to the Upper or Permo-Carboniferous series, and 11,300 feet to the Lower Carboniferous. The productive Coal-measures lie in the upper series. In descending order these are: the Newcastle group, Tomago or East Maitland group, and Greta group. The Permo-Carboniferous series is separated by an unconformability, and a strong break in the flora, from the lower division, in the top of which sheets of andesitic dolerite with tuffs occur.[239] Among the marine strata of the Lower Coal-measure series R. D. Oldham found coarse conglomerates, which he compared with those of India as probably indicative of glacial transport.[240]

In New Zealand the rocks assigned to the Carboniferous system consist, in the upper part, of fine clay-slates, becoming calcareous and passing down into true limestones at the base, from which Spirifer bisulcatus, S. glaber, Productus brachythœrus, etc., have been obtained. They are thus probably Lower Carboniferous; and, though they do not yield coal, they are geologically important from the large share they take in the structure of the great mountain-ranges, and from the occasional abundant development in them of contemporaneous igneous rocks, which are associated with metalliferous deposits.[241]

North America.—Rocks corresponding in geological posi-

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238 See the papers by W. B. Clarke, R. Etheridge jun., De Koninck and Wilkinson cited on p. 1290.

239 Trans. Austral. Assoc. Soc. vol. ii. 1890, pp. 459–465. O. Feistmantel Mem. Geol. Surv. N. S. Wales, Palæontology, No. 3, 1890, p. 37. The Carboniferous and Permo-Carboniferous corals of New South Wales are described by E. Etheridge jun., op. cit. No. 5, 1891. For recent information on the Australian Coal-fields, see papers by Walker, Robertson & Cox, Trans. Fed. Inst. Min. Eng. ii. 1891, pp. 268, 321; iv. 1893, p. 83. For a detailed account of the Permo-Carboniferous rocks and fossils of Queensland, see R. L. Jack and E. Etheridge jun., "The Geology and Palæontology of Queensland," 1892, chaps. vi.–xxii.

240 Rec. Geol. Surv. India, xix. part i. p. 39.

241 Hector's "Handbook of New Zealand," 1883, p. 35. F. W. Hutton, Quart. Journ. Geol. Soc. 1885, p. 200.

tion and the general aspect of their organic contents with the Carboniferous system of Europe are said to cover an area of more than 200,000 square miles in the United States and British North America. The following table shows the subdivisions which have been established among them:

Carboniferous.

Coal-measures—a series of sandstones, shales, ironstones, coals, etc., varying from 100 feet in the interior continental area to 4000 feet in Pennsylvania, and more than 8000 feet in Nova Scotia. The plant remains include forms of Lepidodendron, Sigillaria, Stigmaria, Calamites, ferns and coniferous leaves and fruits. The animal forms embrace in the marine bands species of Spirifer, Productus, Bellerophon, Nautilus, etc. Among the shales and carbonaceous beds numerous traces of insect life have been obtained, comprising species related to the may-fly and cockroach. Spiders, scorpions, centipeds, limuloid crabs and land-snails like the modern Pupa have also been met with. The fish remains comprise teeth and ichthyodorulites of selachian genera, and a number of ganoids (Eurylepis, Cœlacanthus, Megalichthys, Rhizodus, etc.) Several labyrinthodonts occur, and true reptiles are represented by one saurian genus found in Nova Scotia, the Eosaurus.

In the Western Territories the Upper Carboniferous rocks consist of a massive group of limestone 2000 feet thick, resting on Lower Carboniferous ("Weber Quartzite" of King), estimated at 6000 to 10,000 feet, but with no coals.

Millstone Grit—a group of arenaceous and sometimes conglomeratic strata, with occasional coal-seams, only 25 feet thick in some parts of New York, but swelling out to 1500 feet in Pennsylvania.

Sub-Carboniferous.

In the Mississippi basin, where the sub-Carboniferous groups are best developed, they present the following subdivisions in descending order:—

Chester group.—Limestones, shales and sandstones, sometimes 600 feet.

St. Louis group.—Limestones with shale, in places 250 feet.

Keokuk group.—Limestone with chert layers and nodules.

Burlington group.—Limestone, in places with chert and hornstone, 25 to 200 feet.

Kinderhook group.—Sandstones, shales and thin limestones, 100 to 200 feet, resting on the Devonian black shale.

The sub-Carboniferous groups are mainly limestones, but contain here and there remains of the characteristic Carboniferous land vegetation. Crinoids of many forms abound in the limestones. A remarkable polyzoon, Archimedes, occurs in some of the bands. The brachiopods are chiefly represented by species of Spirifer and Productus; the lamellibranchs by Myalina, Schizodus, Aviculopecten, Nucula, Pinna and others; the cephalopods by Orthoceras, Nautilus, Goniatites, Gyroceras, etc. The European genus of trilobite, Phillipsia, occurs. Numerous teeth and fin-spines of selachian fishes give a further point of resemblance to the European Carboniferous Limestone. Some of the rippled rain-pitted beds contain amphibian footprints—the earliest American forms yet known. Large deposits of gypsum occur in this stage in Nova Scotia.

The highest members of the Carboniferous system in the United States are usually barren of coal. The characteristic Lepidodendra and Sigillariæ disappear and their place is taken by plants with Permian affinities (Pennsylvania, Ohio, W. Virginia), while in Illinois, Texas, and New Mexico, Permian reptiles occur in this part of the system. In these regions no definite upper limit to the system can be found, as it shades upward into strata which may represent the Permian series of Europe.[242]

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[242] See Report to the International Geological Congress, London, 1888, by J. J. Stevenson. Full details of the N. American Carboniferous system are given in Correlation Papers—Devonian and Carboniferous, by H. S. Williams, Bull. U. S. Geol. Survey, No. 80, 1891.

Section v. Permian (Dyas)

§ 1. General Characters

THE Carboniferous rocks are overlain, sometimes conformably, but in Europe for the most part unconformably, by a series of red sandstones, conglomerates, breccias, marls, and limestones. These used to be reckoned as the highest part of the Coal formation. In England they received the name of the "*New* Red Sandstone" in contradistinction to the "*Old* Red Sandstone" lying beneath the Carboniferous rocks. The term "Poikilitic" was formerly proposed for them, on account of their characteristic mottled appearance. Eventually they were divided into two systems, the lower being taken as the summit of the Palæozoic series of formations, and the upper as the basement of the Mesozoic. This arrangement, which is mainly based on the difference between the organic remains of the two divisions, is generally adopted by geologists.[243]

Following the usual grouping, we remark that the portion of the red strata classed as Palæozoic has received the name of "Permian," from its wide development in the Russian province of Perm, where it was studied by Murchison, De Verneuil, and Keyserling. In Germany, where it ex-

[243] Some writers, however, still contend that the red rocks of Europe between the summit of the Carboniferous and base of the Jurassic system form really one great series, the break between them being merely local. See for example, H. B. Woodward, Geol. Mag. 1874, p. 385; "Geology of England and Wales," 2d edit. 1887, p. 207, and authorities cited by him.

hibits a well-marked grouping into two great series of deposits, the name "Dyas," proposed by Geinitz, has on that account been to some extent adopted. In North America, where no good line of subdivision can be made at the top of the Carboniferous system, the term "Permo-Carboniferous" has been used to denote the transitional beds at the top of the Palæozoic series, and this name has been proposed for use also in Europe and in Australia.

In Europe two distinct types of the system can be made out. In one of these (Dyas) the rocks consist of two great divisions: (1) a lower series of red sandstones and conglomerates, and (2) an upper group of limestones and dolomites. In the other (Russian or Permian) the strata are of similar character, but are interstratified in such a way as to present no twofold petrographical subdivision.

Rocks.—The prevailing materials of the Permian series in Europe are undoubtedly red sandstones, passing now into conglomerates and now into fine shales or "marls." In their coarsest forms, these detrital deposits consist of conglomerates and breccias, composed of fragments of different crystalline or older Palæozoic rocks (granite, diorite, gneiss, mica-schist, quartzite, graywacke, sandstone, etc.), that vary in size up to blocks a foot or more in diameter. Sometimes these stones are well rounded, but in many places they are only partially so, while, here and there, they are quite angular, and then constitute breccias. The pebbles are held together by a brick-red ferruginous, siliceous, sandy, or argillaceous cement. The sandstones are likewise characteristically brick-red in color, generally with green or white layers and spots of decoloration. The "marls," showing still deeper shades of red, and passing occasionally into a kind of livid purple, are crumbling sandy clay-rocks, some-

times merging into more or less fissile shales. Of the argillaceous beds of the system the most remarkable are those of the Marl-slate or Kupferschiefer—a brown or black often distinctly bituminous shale, which in certain parts of Germany is charged with ores of copper. The limestone, so characteristic a feature in the "Dyas" development of the system, is a compact, well-bedded, somewhat earthy, and usually more or less dolomitic rock (Zechstein). It is the chief repository of the Permian invertebrates. With it are associated bands of dolomite, either crystalline and cavernous (Rauchwacke) or finely granular and crumbling (Asche); also bands of gypsum, anhydrite, and rock-salt. In certain localities (the Harz, Bohemia, Autun) seams of coal are intercalated among the rocks, and with these, as in the Coal-measures, are associated bituminous shales and nodular clay-ironstones. In Germany, France, the southwest of England, and the southwest of Scotland, the older part of the Permian system contains abundant contemporaneous masses of eruptive rock, among which occur diabase, melaphyre, porphyrite, and various forms of quartz-porphyry.

Some of the breccias in the west of England contain striated stones, which, according to Sir A. C. Ramsay, indicate the existence of glaciers in Wales during the Permian period.[244]

The Permian system in the greater part of Europe, from the prevalent red color of its rocks, the association of dolomite, rock-salt, saliferous clays, gypsum, and anhydrite, and the remarkably impoverished and stunted aspect of its fauna, has evidently been deposited in isolated basins in which the

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[244] Quart. Journ. Geol. Soc. 1855, p. 185.

water, cut off more or less completely from the sea, underwent concentration until chemical precipitation could take place. Looking back at the history of the Carboniferous rocks, we can understand how such a change in physical geography was brought about. The Carboniferous Limestone sea having been by upheaval excluded from the region, wide lagoons occupied its site, and these, as the land slowly went down, crept over the old ridges that had for so many ages been prominent features. The downward subterranean movement was eventually varied by local elevations, and at last the Permian basins came to be formed. As a result of these disturbances, the Permian rocks overlap the Carboniferous, and even cover them in complete discordance, the denudation of the older formation having been, in some places, enormous before the Permian strata were laid down.[245]

In Southern Europe and thence eastward, abundant evidence of open seas is supplied by limestone containing a rich fauna of foraminifera, gasteropods, orthoceratites, and early precursors of the ammonites.

LIFE.—The conditions under which the Permian rocks of the greater part of Europe were deposited must have been eminently unfavorable to life. Accordingly we find that these rocks are on the whole singularly barren of organic remains. So great is the contrast between them and older formations, that instead of such rich faunas as those of the Silurian, Devonian, and Carboniferous systems, they have yielded only somewhere about 300 species of organisms.

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245 In some places, the whole of the Carboniferous system has been worn away down to the Carboniferous Limestone, upon which the Permian sandstones and conglomerates have been directly deposited. The discordance, however, sometimes disappears, and then the Carboniferous and Permian rocks shade into each other.

The flora of the older Permian rocks presents many points of resemblance to the Carboniferous.[246] According to Grand' Eury, upward of 50 species of plants are common to the two floras. Among the forms which rise into the Permian rocks and disappear there, are Calamites Suckowii, C. approximatus, Asterophyllites equisetiformis, A. rigidus, Pecopteris elegans, Odontopteris Schlotheimii, Sigillaria, Brardii (and others), Stigmaria ficoides, Cordaites borassifolius, etc. Others, which are mainly Permian, are yet found in the highest coal-beds of France, *e.g.* Calamites gigas, Calamodendron striatum, Arthropitus ezonata, Tæniopteris abnormis, Walchia piniformis, etc. But the Permian flora has some distinctive characters; such as the variety and quantity of the ferns united under the genus Callipteris, which do not occur in the Coal-measures, the profusion of tree-ferns (Psaronius, of which 24 species are described by Goppert, Protopteris, Caulopteris, etc.) of Equisetites, and of the conifers Walchia piniformis and W. filiciformis, and the occurrence of species of Gingko. The most characteristic plants throughout the German Permian groups are Odontopteris obtusiloba, Callipteris conferta, Calamites gigas, and Walchia piniformis. The last representatives of the ancient tribes of the lepidodendra, sigillarioids, and calamites are found in the Permian system. Cycads now make their appearance and increase in importance in the succeeding geological periods. Among their Permian forms are the genera Pterophyllum and Medullosa. In extra-European Permian areas a commingling of Palæozoic and Mesozoic types of vegetation has been observed, forms of Voltzia, Pterophyllum, and Glossopteris being there prominent.

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[246] See Göppert's "Die Fossile Flora der Permischen Formation," Cassel, 1864–65.

The impoverished fauna of the Permian rocks of central Europe is found almost wholly in the limestones and brown shales, the red conglomerates and sandstones being, as a rule, devoid of organic contents. A few corals (Stenopora, Polycœlia) and polyzoa (Fenestella, Polypora, Synocladia, Acanthocladia) occur in the limestones, the latter sometimes even in continuous masses like coral-reefs, as in the dolomite-reef of S.E. Thuringia. The echinoderms are few, the chief crinoids being species of Cyathocrinus. Among the

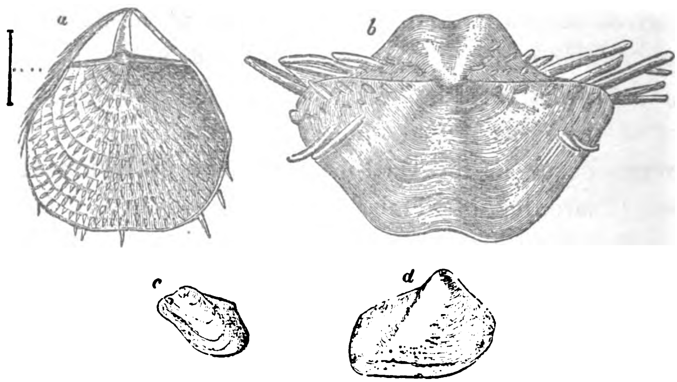

Fig. 374.—Permian Mollusks.
a, Strophalosia Goldfussi, Munst. (enlarged); *b*, Productus horridus, Sow.; *c*, Bakevellia tumida, King; *d*, Axinus (Schizodus) Schlotheimii, Geinitz.

brachiopods, of which some 30 species are known, the most conspicuous are forms of Productus, Camarophoria, Spirifer, Strophalosia (Fig. 374), and Aulosteges. Lamellibranchs are more numerous, characteristic genera in the German limestone being Axinus (Fig. 374), Allorisma, Solemya, Schizodus, Edmondia, Arca, Avicula, Bakevellia (Fig. 374), Pecten. Among the few gasteropods, forms of Chemnitzia, Turbo, Murchisonia, Pleurotomaria, and Chiton have been recorded. An occasional Nautilus, Orthoceras, or Cyrto-

ceras represents the rich cephalopodan fauna of the Carboniferous Limestone.

It is not, however, from the sites of the brackish inland seas of western and central Europe that we may obtain the best conception of the animal life of Permian time. If we pass southward into the Alps and the Mediterranean basin or eastward into the Uralian region and thence into India, we find that while some of the European forms extend into these areas, they are accompanied by many hundreds of other species. One of the most remarkable features in this richer and more varied fauna is the great number of cephalopods and the affinities which many of them present to the Ammonites

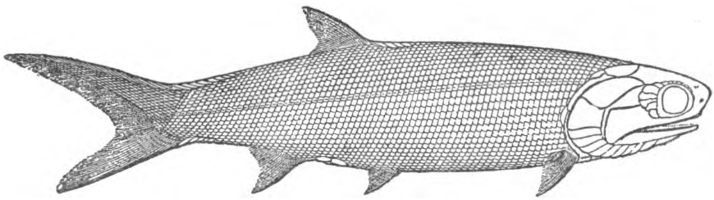

Fig. 375.—Palæoniscus macropomus, Ag. (½), Kupferschiefer. From a restoration by Dr. Traquair.

so characteristic of Mesozoic time. Among the Permian genera of this type are Adrianites, Arcestes, Medlicottia, Popanoceras, Stacheoceras, Thalassoceras, and Waagenoceras. They are associated with many forms of Orthoceras, Gyroceras, and Nautilus—a blending of Palæozoic and Mesozoic types which is much less clearly shown in central and western Europe.

Fishes, which are proportionately better represented in the Permian rocks than the invertebrates, chiefly occur in the marl-slate or Kupferschiefer, the most common genera being Palæoniscus (Fig. 375), which is specially characteris-

tic, Platysomus (Fig. 376), Pygopterus, Acanthodes, Acrolepis, Amblypterus.

Amphibian life appears to have been abundant in Permian times, for some of the sandstones of the system are covered with footprints, assigned to the extinct order of Labyrinthodonts. Occasional skulls and other bones have been met with referable to Archegosaurus, Lepidotosaurus, Zygosaurus, etc. The remains of comparatively few forms, however, had been found until the remarkable discoveries

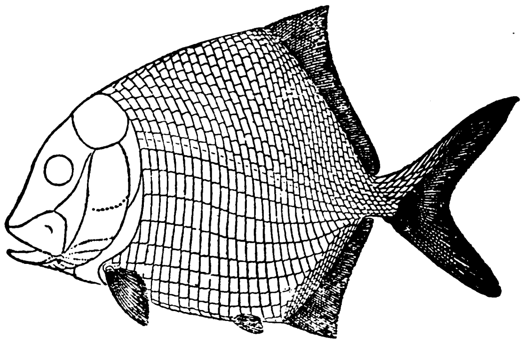

Fig. 376.—Platysomus striatus, Ag. (½), Magnesian Limestone. Restored by Dr. Traquair.

of Dr. Anton Fritsch in the basins of Pilsen and Rakowitz in Bohemia. The strata of these localities have been already (p. 1386) referred to as containing an abundant and characteristic coal-flora, yet with a fauna that is as decidedly like that of known Permian rocks. According, therefore, as we give preference to the plants or the animals, the strata may be ranked as Carboniferous or as Permian. Of the numerous Saxon and Bohemian species of amphibians, Prof. Credner in Dresden and Dr. Fritsch in Prague have published elaborate descriptions. Among the genera are Protriton

(Branchiosaurus), a form resembling an earth-salamander in possessing gills, and of which the largest specimen is only about 2½ inches long, Sparodus, Hylonomus, Dawsonia, Melanerpeton, Dolichosoma, Ophiderpeton, Macromerion, Urocordylus, Limnerpeton, Hyloplesion, Seeleya, Microbrachis, Diplospondylus, Nyrania, and Dendrerpeton. Some of these forms were remarkably small. The adult Protritonidæ, for instance, were only from 2½ to 6½ inches long. Other types, however, attained a much larger size, Palæosiren, for instance, being estimated to have had a length of 45 feet.[247] From the corresponding strata of Autun in central France, M. Gaudry has also described some interesting forms—Actinodon, Protriton, Euchirosaurus, a larger and more highly organized type than any previously known from the Palæozoic rocks of France, but inferior to another subsequently found at Autun, which he has named Stereorhachis, and which was distinguished by completely ossified vertebræ and other proofs of higher organization that connect it with the Theriodonts of Russia and Southern Africa and with the Pelycosaurians of the United States.[248] Various other anomodont reptiles have been met with, referable to a number of genera (Naosaurus, Clepsydrops). Of still higher grade were other types to which the names Proterosaurus and Palæohatteria (Rhynchocephalia) have been given.

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247 A. Fritsch, "Fauna der Gaskohle und der Kalksteine der Permformation Böhmens," Prag. 1881. See also H. Credner on Stegocephali from the Rothliegende of Dresden, Z. Deutsch. Geol. Ges. 1881–86; E. D. Cope, Amer. Nat. xviii. 1884.

248 Gaudry, Bull. Soc. Geol. France, vii. (3 ser.) p. 62; ix. p. 17; xiii. p. 44; xiv. pp. 430, 444. "Les Enchaînements du Monde Animal," 1883, Arch. Mus. Nat. Paris, x. 1887.

§ 2. Local Development

Britain.[249]—In England on a small scale, a representative is to be found of the two contrasted types of the European Permian system. On the east side of the island, from the coast of Northumberland southward to the plains of the Trent, a true "Dyas" development is exhibited, the Magnesian Limestone and Marl Slate forming the main feature of the system; on the west side of the Pennine chain, however, the true Permian or Russian facies is presented. The system is in this country most nearly complete in the north-western and southwestern counties of England. Arranged in tabular form the rocks of the western and eastern areas may be grouped as follows:

	W. of England	E. of England
Red sandstones, clays, and gypsum . .	600 ft.	50–100 ft.
Magnesian Limestone . . . . . Marl Slate	10–30 "	600 "
Lower red and variegated sandstone, reddish brown and purple sandstones and marls, with calcareous conglomerates and breccias	3000 "	100–250 "

Lower Sandstone.—This subdivision attains its greatest development in the vale of the Eden, where it consists of brick-red sandstones, with some beds of calcareous breccia, locally known as "brockram," derived principally from the waste of the Carboniferous Limestone. These red rocks extend across the Solway into the valleys of the Nith and Annan in the south of Scotland, where they lie unconformably on the Lower Silurian rocks, from which their breccias have generally been derived, though near Dumfries they contain some "brockram." The breccias have evidently accumulated in small lakes or narrow

[249] Sedgwick, Trans. Geol. Soc. (2) iii. 1835, p. 37; iv. 383; De la Beche, "Geology of Cornwall, Devon," etc. p. 193; Murchison, "Siluria," p. 308; W. King, "Monograph of the Permian Fossils," Palæontog. Soc. 1850; Hull, "Triassic and Permian Rocks of Midland Counties of England," in Mem. Geol. Surv. 1869; Q. J. Geol. Soc. xxv. 171; xxix. p. 402; xlviii. p. 60; Ramsay, op. cit. xxvii. p. 241; Kirkby, op. cit. xiii. xvi. xvii. xx.; E. Wilson, op. cit. xxxii. p. 533; D. C. Davies, op. cit. xxxiii. p. 10; H. B. Woodward, Geol. Mag. 1874, p. 385; "Geology of England and Wales," p. 210; T. V. Holmes, Q. J. Geol. Soc. xxxvii. p. 286; W. T. Aveline, H. H. Howell in various Memoirs Geol. Surv.

fjords. In the basin of the Nith, and also in Ayrshire, numerous small volcanic vents and sheets of diabase, picrite, olivine-basalt, porphyrite and tuff are associated with the red sandstones, marking a volcanic district of Permian age. The vents rise through Coal-measures as well as more ancient rocks. Similar vents in Fifeshire, also piercing Coal-measures, have been referred to the same volcanic period. In Devonshire similar rocks mark the outpouring of lavas in the early part of the Permian period.[250] But these volcanic phenomena were on a feeble scale. They are interesting as marking the close of the long continuance of volcanic activity during Palæozoic time. Neither in Britain nor throughout most of the Continent has evidence been found of renewed eruptions during the long lapse of the Mesozoic ages.[251]

In central England, Staffordshire, and the districts of the Clent and Abberley Hills, the Permian system contains some remarkable brecciated conglomerates which attain a thickness of 400 feet. They have been shown by Ramsay[252] to consist in large measure of volcanic rocks, grits, slates, and limestones, which can be identified with rocks on the borders of Wales. Some of their blocks are three feet in diameter and show distinct striation. These Permian drift-beds, according to Ramsay, cannot be distinguished by any essential character from modern glacial drifts, and he had no doubt that they were ice-borne, and, consequently, that there was a glacial period during the accumulation of the Lower Permian deposits of the centre of England.

Like red rocks in general, the Lower Permian beds are almost barren of organic remains. Such as occur are indicative chiefly of terrestrial surfaces. Plant remains occasionally appear, such as Ullmannia (supposed to be of marine growth), Lepidodendron dilatatum, Calamites, Sternbergia, Dadoxylon, and fragments of coniferous wood. The cranium of a labyrinthodont (Dasyceps) has been obtained from the Lower Permian rocks at Kenilworth. Footprints, referred to members of the same extinct order, have been observed abundantly on the surfaces of the sandstones of Dumfriesshire, and also in the vale of the Eden.

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250 Geol. Mag. 1866, p. 243; Quart. Journ. Geol. Soc. 1892, Presid. Address, p. 147, and authorities cited.

251 Op. cit. p. 162.

252 Q. J. Geol. Soc. xi. p. 181.

Magnesian Limestone Group.—This subdivision is the chief repository of fossils in the Permian system of England. Its strata are not red, but consist of a lower zone of hard brown shale with occasional thin limestone bands (Marl Slate) and an upper thick mass of dolomite (Magnesian Limestone). The latter is the chief feature in the Dyas development of the system in the east of England. Corresponding with the Zechstein of Germany, as the Marl Slate does with the Kupferschiefer, it is a very variable rock in lithological characters, being sometimes dull, earthy, fine-grained, and fossiliferous, in other places quite crystalline, and composed of globular, reniform, botryoidal, or irregular concretions of crystalline and frequently internally radiated dolomite. It is divisible in Durham into three sections—1st, Lower compact limestone, about 200 feet thick; 2d, Middle fossiliferous and brecciform limestone, 150 feet; 3d, Upper yellow concretionary and botryoidal limestone, 250 feet. The Magnesian Limestone runs as a thick persistent zone down the east of England.[953] In southern Yorkshire it is split up by a central zone of marls and sandstones with gypsum. It is represented on the Lancashire, Cheshire, and Cumberland (Penrith) side by bright red and variegated sandstones covered by a thin group of red marls, with numerous thin courses of limestone, containing Schizodus, Bakevellia, and other characterstic fossils of the Magnesian Limestone. Murchison and Harkness have classed as Upper Permian certain red sandstones with thin partings of red shale, and an underlying band of red and green marls and gypsum. These rocks, seen at St. Bees, near Whitehaven, resting on a magnesian limestone, have not as yet yielded any fossils.

The Magnesian Limestone group of the north of England has yielded about 150 species belonging to some 70 genera of fossils—a singularly poor fauna when contrasted with that of the Carboniferous system below. The brachiopods include Productus horridus, Camarophoria humbletonensis, C. Schlotheimii, Strophalosia Goldfussi, Lingula Credneri, and Terebratula elongata. Of the lamellibranchs Axinus (Schizodus) Schlotheimii, Bakevellia tumida, B. antiqua,

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[953] In borings at Middlesboro' beds of salt and gypsum have been found at a depth of more than 1300 feet from the surface, and below a mass of limestone 67 feet thick, which is believed to be the Magnesian Limestone.

B. ceratophaga, Mytilus squamosus, and Arca striata are characteristic. The univalves are represented by 10 genera and 26 species, including Pleurotomaria and Turbo as common genera. Nine genera of fishes have been obtained chiefly in the Marl Slate, of which Palæoniscus and Platysomus are the chief. These small ganoids are closely related to some which haunted the lagoons of the Carboniferous period. Some reptilian remains have been obtained from the Marl Slate, particularly Proterosaurus Speneri and P. Huxleyi, while Lepidotosaurus Duffii has been found in the Magnesian Limestone.

Fine sections are exposed on the south coast of Devonshire of coarse breccias and red sandstones, which have been assigned by some writers to the Trias, by others to the Permian series. They rest unconformably on Devonian strata, and have been derived from the degradation of these rocks. At many places in the interior to the west of Exeter bands of basic amygdaloidal lavas are intercalated in them, like the volcanic sheets in the Permian sandstones of Scotland. Owing to the apparent passage of these red strata upward into others which graduate into the base of the Lias, and are undoubtedly Triassic, the whole series of red sediments has not unnaturally been regarded as referable to the Trias. The resemblance of the lower parts of the series to Permian rocks, coupled with the occurrence of volcanic bands in them, has more recently been held to justify the separation of these lower breccias and sandstones from the rest as representatives of the Permian series of the Midlands.[254]

Germany, etc.[255]—The "Dyas" type of the system attains a great development along the flank of the Harz Mountains, also in the Rhine province,[256] Thuringia, Saxony, Bavaria,

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[254] Hull, Quart. Journ. Geol. Soc. xlviii. 1892, p. 60; A. Irving, op. cit. xliv. 1888 and xlviii. p. 68.

[255] H. B. Geinitz, "Die animalischen Ueberreste der Dyas," 1861–62, Suppl. 1880–82; "Zur Dyas in Hessen," Festsch. Ver. f. Naturk. Cassel, 1886; Geinitz and Gutbier, "Die Versteinerungen des Zechsteinsgebirge," etc. 1848–49; C. E. Weiss, "Fossile Flora der jüngst. Steinkohlenf. und des Rohliegend." etc. 1869–72. Much recent information will be found in the publications of the Geological Surveys of Prussia, Saxony and Alsace-Lorraine. See, for example, E. W. Benecke and L. van Wervecke, Mitth. Geol. Landesanst. Elsass-Lothr. iii. part i. 1890.

[256] For an account of the Permian development in this region, see especially H. von Dechen, "Geolog. und Palæont. Uebersicht der Rheinprovinz und der Provinz Westfalen," Bonn, 1884, p. 291.

and Bohemia. On the south side of the Harz it is grouped into the following subdivisions:

Zechstein Group	Upper	Anhydrite, gypsum, rock-salt, marl, dolomite, fetid shale, and limestone. The amorphous gypsum is the chief member of this group; the limestone is sometimes full of bitumen.
	Middle	Crystalline granular (*Rauchwacke*) and fine powdery (*Asche*) dolomite (sometimes 150 feet thick, with gypsum at the bottom).
	Lower	Zechstein-limestone, an argillaceous thin-bedded compact limestone 15 to 30 (sometimes even 90) feet thick.
		Kupferschiefer—a black bituminous shale not more than about 2 feet thick.
		Zechstein-conglomerate, and calcareous sandstone.
Rothliegende Group	Upper	Red sandstone (*Kreuznach*), red shales (*Monzig*), with sheets of melaphyre and masses of quartz-porphyry conglomerate (*Sötern*).
	Lower	Sandstones and conglomerates lying on black shales with poor coal-seams (*Lebach*).
		Sandstones and shales, with some seams of coal resting on red and gray sandstones with bands of impure limestone (*Cusel*).

The name "Rothliegende," or rather "Rothtodtliegende" (red-layer or red-dead-layer), was given by the miners because their ores disappeared in the red rocks below the copper-bearing Kupferschiefer. The coarse conglomerates have been referred by Ramsay to a glacial origin, like those of the Abberley Hills. They attain the enormous thickness of 6000 feet or more in Bavaria. One of the most interesting features of the formation is the evidence of the contemporaneous outpouring of great sheets of quartz-porphyry, granite-porphyry, porphyrite, and melaphyre, with abundant interstratifications of various tuffs, not infrequently inclosing organic remains. From the very nature of its component materials, the Rothliegende is comparatively barren of fossils; a few ferns, calamites, and remains of coniferous trees are found in it, particularly in the lower part of the group, where they form thin seams of coal.

The plants, all of terrestrial growth, on the whole resemble generically the Carboniferous flora, but seem to be nearly all specifically distinct. They include forms of Calamites (C. gigas), Asterophyllites, and ferns of the genera Callipteris (C. conferta), Sphenopteris, Alethopteris, Neuropteris, Odontopteris, with well-preserved silicified stems of tree-ferns (Psaronius, Tubicaulis). The conifer Walchia (W. piniformis) is specially characteristic. Fish remains occur sparingly (Amblypterus, Palæoniscus, Acanthodes), while labyrinthodonts have been met with in the Dresden district in considerable number and variety.

The Zechstein group is characterized by a suite of fossils

like those of the Magnesian Limestone group of England. The Kupferschiefer contains numerous fish (Palæoniscus Freieslebeni, Platysomus gibbosus, etc.). This deposit is believed to have been laid down in some inclosed sea-basin, the waters of which, probably from the rise of mineral springs connected with some of the volcanic foci of the time, were so charged with metallic salts in solution as to become unfit for the continued existence of animal life. The dead fish, plants, etc., by their decay, gave rise to reduction and precipitation of these salts as sulphides, which thereupon inclosed and replaced the organic forms, and permeated the mud at the bottom. This old sea-floor is now the widely-extended band of copper-slate which has so long and so extensively been worked along the flanks of the Harz. After the formation of the Kupferschiefer the area must have been once more covered with clearer water, for the Zechstein Limestone contains a number of organisms, among which Productus horridus, Spirifer undulatus, Strophalosia Goldfussi, Terebratula elongata, Camarophoria Schlotheimii, Schizodus obscurus, and Fenestella retiformis are common. Renewed unfavorable conditions are indicated by the dolomite, gypsum, and rock-salt which succeed. Reasoning upon similar phenomena as developed in England, Ramsay has connected them with the abundant labyrinthodont footprints and other evidences of shores and land, as well as the small number and dwarfed forms of the shells in the Magnesian Limestone, and has speculated on the occurrence of a long "continental period" in Europe, during one epoch of which a number of salt inland seas existed wherein the Permian rocks were accumulated. He compares these deposits to what may be supposed to be forming now in parts of the Caspian Sea.

Some of the deposits of the Zechstein in Germany have a great commercial value. The beds of rock-salt are among the thickest in the world. At Sperenberg, near Berlin, one has been pierced to a depth of nearly 4000 feet, yet its bottom has not been reached. Besides rock-salt and gypsum there occur with those deposits thick masses of salts of potash (Carnallite) and magnesia (Kieserite) and other salts.

In Bohemia (pp. 1356, 1386, 1400) and Moravia, where the Permian system is extensively developed, it has been divided into three groups. (1) A lower set of conglomerates, sandstones, and shales, sometimes bituminous. These strata contain diffused copper ores, and abound here and

there in remains of land-plants and fishes. (2) A middle group of felspathic sandstones, conglomerates, and micaceous shales, with vast numbers of silicified tree-stems (Araucarites, Psaronius). (3) An upper group of red clays and sandstones, with bituminous shales. Eruptive rocks (melaphyre, porphyrite, etc.) are associated with the whole formation. The Zechstein is here absent. In place of the marine shells, crinoids and corals so characteristic of that formation, the Bohemian Permian strata have yielded the remarkable series of amphibian remains already alluded to, together with abundant traces of the land of the period, such as remains of orthopterous insects, scorpions, millipeds, and a rich terrestrial flora (Sphenopteris, Neuropteris, Odontopteris, Pecopteris, Alethopteris, Callipteris conferta, Schizopteris, Calamites, Asterophyllites, Sphenophyllum, Lepidodendron, Sigillaria, Walchia, Araucaryoxylon).

Vosges.—In this region the following succession of strata has been assigned to the Permian system:

4. Kohlbachel group of red arkoses, felspathic sandstones, shales, conglomerates, breccias, and dolomite, 500 to 600 feet, with intercalated sheets of melaphyres and tuffs.
3. Variegated tuffs and marls of Meisenbuckel.
2. Dark shales, limestones, and dolomites of Heisenstein.
1. Arkose and shale (Callipteris conferta), with conglomerate (sometimes 150 feet thick), containing blocks of porphyry, gneiss, quartz, etc., filling up hollows of the crystalline schists on which they lie unconformably.

The existence of volcanic action during Permian time in this region is shown by the presence of interstratified basic lavas, and by the great quantity of fragments of quartz-porphyry in the conglomerates, which have been compared to volcanic agglomerates.[257]

France.—Permian rocks occur in many detached areas in

[257] Benecke and Van Wervecke, Mitth. Geol. Landesanst. Elsass-Loth. vol. iii. 1890, p. 45; Velain, Bull. Soc. Geol. France, ser. 3, xiii.; Eck, "Geogn. Karte d. Ung. von Lahr." 1884; "Geogn. Karte v. Schwartzwald." 1887. A full bibliography for Alsace and Lorraine will be found in Abth. Geol. Specialkart. v. Elsass-Lothringen, vol. i. 1875 and vol. for 1887.

France. In the central plateau they are found most fully developed, resting upon and passing down into the higher parts of the Carboniferous system. They have been carefully studied in the district of Autun, where the lower part of the Permian system is represented by a mass 900 to 1000 metres thick of alternations of sandstone and shale more or less rich in hydrocarbons, with thin bands of magnesian limestone. No marine fossils occur in these strata, even the magnesian limestone containing only fresh-water organisms. From the distribution of the fossils a threefold stratigraphical subdivision of the whole series has been made. 1st, A lower group at least 150 to 200 metres thick, lying conformably upon the Coal-measures, and containing numerous ferns (Pecopteris, abundant), Sigillariæ, Syringodendra, Cordaites, a profusion of Walchia, large numbers of seeds or fruits, cyprids crowded in some layers of shale, an amphipod (Nectotelson), a number of fishes (Palæoniscus, Amblypterus, Acanthodes, Pleuracanthus), and the amphibians and reptiles already referred to (Actinodon, Euchirosaurus, Stereorhachis). 2d, A middle group about 300 metres thick, showing a cessation of the characteristically Carboniferous species of plants, and an increasing prominence of typically Permian forms. Numerous species of Pecopteris still occur, but Callipteris makes its appearance (C. conferta, C. gigantea). Walchia (W. piniformis, W. hypnoides), Calamites, Sphenophyllum, Calamodendron, and fruits abound. The animal remains resemble those of the lower group, but with the addition of Protriton and Pleuroneura. 3d, An upper group locally known as that of the "Boghead," from a workable band of bituminous shale or coal.[258] The thickness of this group is about 500 metres, the upper portion consisting of red sandstones without fossils. The flora is now markedly Permian. Pecopterid ferns are rare, and are specifically distinct from those in the group below. There is an abundance and variety of Callipteris, together with Sigillaria, abundant Walchia and Asterophyllites, Piceites, Sphenophyllum, Carpolithes, etc. The fauna is generally similar to that in the middle group, but less varied.[259]

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[258] "Boghead," so named from a place in Linlithgowshire, Scotland, where the substance was first worked for making gas and oil. The so-called "Boghead" of Autun has been ascertained to contain a large quantity of the remains of gelatinous fresh-water algæ mingled with the pollen of Cordaites; B. Renault and E. Bertrand, Soc. Hist. Nat. Autun, 1892.

[259] E. Roche, Bull. Soc. Geol. France, ser. 3, ix. 1880, p. 78. See also the

In the extreme south of France, between Toulon and Cannes, Permian rocks reappear, and, though occupying but a limited area, constitute some of the most picturesque features along the Mediterranean shores of the country. They consist of lower massive conglomerates, with intercalations of shale, containing Walchia and Callipteris, followed by shales, marls, red sandstones, and conglomerates. But their distinguishing feature is the enormous mass of volcanic materials associated with them. The lower conglomerates, besides their fragments of gneiss derived from the pre-Cambrian rocks of the district, contain abundant pieces of quartz-porphyry, of which rock also there are massive sheets, which rise up into the well-known group of hills forming the Esterel between Cannes and Fréjus. Besides these acid outbursts in the older part of the formation, sheets of melaphyre are found in the upper part, while dikes of nodular felsite, pitchstone, and melaphyre traverse the series.[260]

Westward in the region of the Pyrenees, and in various parts of the Iberian peninsula, rocks believed to be Permian have been recognized. They frequently present thick masses of conglomerate, sometimes resting upon Carboniferous rocks, sometimes on formations of older date.

Alps.[261]—On both sides of the Alpine chain a zone of conglomerates and sandstones, which intervenes between the Trias and older rocks of the region, has been referred to the Permian system. The conglomerates (Verrucano conglomerate) are made up of the detritus of schistose rocks, porphyries, quartz, and other materials of the central core of the mountains. They sometimes contain sheets of porphyry, and occasionally, as at Botzen, they are replaced by vast masses of quartz-porphyry and other volcanic rocks, with

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series of "Études des Gîtes Mineraux," published by the Ministry of Public Works in France, particularly the volumes by Delafond on the Autun basin, and by Mouret on that of Brive; likewise the Memoirs by Grand' Eury already cited; Bergeron, "Étude Geologique du Massif au sud du Plateau Central," and Bull. Soc. Geol. France, 3 ser. vol. xvi. Reinach, Zeitsch. Deutsch. Geol. Ges. 1892, p. 23, gives a careful comparison of the French central plateau Permian rocks with those of the Saar and Nahe.

260 F. Walleraut, "Étude Strat. Pétrog. des Maures et de l'Esterel," 1889. Carte Detaill. Geol. France, Feuille d'Antibes.

261 E. Suess, Sitzb. Akad. Wien. lvii. 1868, pp. 230, 763; G. Stache, Zeitsch. Deutsch. Geol. Ges. xxxvi. 1884, p. 367; Jahrb. k. k. Geol. Reichsanst. xxvii. 1877, p. 271, xxviii. 1878, p. 93 (giving the fauna of the Bellerophon Limestone); Verhand. k. k. Geol. Reichsanst. 1888, p. 320; E. Mojsisovics, "Die Dolomit-Riffe von Südtirol und Venetien," 1879, chap. iii.; Fraas, "Scenerie der Alpen."

tuffs and volcanic conglomerates, indicating vigorous volcanic action. An intercalated zone of shales in the lower conglomeratic and volcanic part of the series in the Val Trompia has yielded Walchia piniformis, W. filiciformis, Schizopteris fasciculata, Sphenopteris tridactylites, etc., and serves to mark the Permian age of the rocks. Eastward, at Funfkirchen, in Hungary, in a corresponding position below the Verrucano conglomerate, a group of younger Permian plants has been found, including species of Baiera, Ullmannia, Voltzia, Schizolepis, and Carpolithes, nearly half of which occur also in the German Kupferschiefer. Above the conglomerate or the porphyry comes a massive red sandstone called the "Groden Sandstone," containing carbonized plant-remains. But the most distinctive and interesting feature in the Alpine development of the Permian system is found in the upper portion of the series in the southern region of Tyrol and Carinthia. The red Groden sandstone is there succeeded by beds of gypsum, rauchwacke, and dolomite, above which comes a bituminous limestone known, from the abundance of species of Bellerophon, as the "Bellerophon Limestone." This calcareous member is highly fossiliferous. It contains an abundant marine fauna, which includes ten species of Bellerophon, and species of Nautilus, Natica, Pecten, Aviculoptecten, Avicula, Bakevellia, Schizodus, Spirifer (7 species), Spirigera, Streptorhynchus, Orthis, Strophomena, Leptæna, Productus, and Fusulina. Nearly all these are peculiar species, but the Schizodus, Bakevellia, and Natica connect the assemblage with that of the Zechstein.

It is interesting to trace in this Bellerophon Limestone an indication of the distribution of the more open sea of Permian time in the European area. While the Zechstein was in course of deposition in isolated Caspian-like basins across the centre of the Continent, calcareous sediments were accumulated on the floor of a wider sea which, lying to the south, stretched over the site of the present Mediterranean, eastward across Russia and the heart of Asia. A portion of this sea-floor has been detected in Sicily, where near Palermo M. Gemmellaro has described the abundant fauna found in its limestones. Foraminifera (Fusulina) abound in these rocks, but their most remarkable feature is the number and variety of their cephalopods, which, besides Palæozoic types (Goniatites, Orthoceratites), comprise many new forms (17 genera and 54 species) akin to the tribe of Mesozoic Ammonites (Adrianites, Agathiceras, Cyclolobus, Daraelites,

Gastrioceras, Medlicottia, Parapronorites, Popanoceras, Stacheoceras, Waagenoceras), also gasteropods (Bellerophon, Pleurotomaria, etc.) and brachiopods.[262]

Russia.[263]—The Permian system attains an enormous development in Eastern Europe. Its nearly horizontal strata cover by far the largest part of European Russia. They lie conformably on the Carboniferous system, and consist of sandstones, marls, shales, conglomerates, limestones (often highly dolomitic), gypsum, rock-salt, and thin seams of coal. In the lower and more sandy half of this series of strata remains of land-plants (Calamites gigas, Cyclopteris, Pecopteris, etc.), fishes (Palæoniscus), and labyrinthodonts occur, but some interstratified bands yield Productus Cancrini and other marine shells. The rocks are over wide regions impregnated with copper ores. The upper half of the series consists of clays, marls, limestones, gypsum, and rock-salt, with numerous marine mollusca like those of the Zechstein (Productus Cancrini, P. horridus, Camarophoria Schlotheimii), but with a rather more abundant fauna, and with intercalated bands containing land-plants.

Much attention has been given in recent years to these rocks, which have now been brought into closer comparison with those of other regions. As developed on the western slope of the Ural Mountains, they have been found to consist of the following groups of strata:

> Red clays and marls, with intercalated sandstones and limestones, almost wholly unfossiliferous, but with a few lamellibranchs resembling Unio (Anthracosia) castor and U. umbonatus. This thick group may possibly be partly or wholly Triassic.
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> Copper-bearing sandstone, permeated with oxide and sulphide of copper, and containing species of Calamites (gigas), Sphenopteris (lobata, erosa), Callipteris (obliqua, conferta), Noggerathia, Dadoxylon, Knorria, etc.
>
> Marls, sandstones, and conglomerates with ill-preserved plants (which seem to be on the whole like those of the Artinsk group below), Unio castor, U. umbonatus, U. Goldfussiana, Archegosaurus, Acrolepis, while

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262 Prof. Gemmellaro, "La Fauna dei Calcari con Fusulina," etc., Palermo, 1887–89.

263 See for the earliest descriptions "Russia and Ural Mountains," Murchison, De Verneuil and Keyserling, 4to, 2 vols. 1845.

some of the sandy marls contain a characteristically marine fauna, Productus Cancrini, P. koninckianus, Athyris pectinifera, and Spirifer lineatus.

Gypseous limestones and dolomites.

Artinsk group of sandstones, conglomerates, shales, marls, limestones, and dolomites, stretching from the Arctic Ocean to the Kirgiz Steppes, and lying conformably on the Carboniferous Fusulina Limestone. This group contains a remarkably abundant and varied assemblage of fossils. The plants include species of Calamites, Noggerathia, Sphenopteris, Odontopteris, etc. The fauna comprises a number of common Carboniferous shells such as Productus semireticulatus, P. cora, P. longispinus, P. scabriculus, Streptorhynchus crenistria, but with these are found many new types of cephalopods like the ammonoid forms above alluded to as occurring in the Bellerophon Limestone of the Tyrol (Agathiceras, Gastrioceras, Medlicottia, Popanoceras, Pronorites). About 300 species of fossils have been found in the group, of which a half also occur in the Carboniferous system, and only about a sixth in the Permian above.[264]

Asia.—The type of sedimentation found in the east and south of Europe extends into Asia. In the valley of the Araxes a limestone occurs containing Productus horridus, Athyris subtilita, and a number of the ammonoid forms above referred to; while in Bokhara other limestones occur at Darwas which from their cephalopods (Pronorites, Popanoceras, etc.) probably represent the Artinsk group of Russia. The same character of deposits and of palæontology is still more extensively developed in the Salt Range of the Punjab. In this region the ancient Palæozoic sediments with their saliferous deposits are overlain by a remarkable limestone which has yielded a large assemblage of fossils. At the base of this deposit comes a coarse conglomerate and sandstones followed by the well-known Productus Limestone.[265] The lower portions of the limestone abound in

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264 A. Krasnopolsky, Mem. Com. Geol. Russ. xi. 1889, No. 1; A. Karpinsky, Verhand. k. Min. Gesell. St. Petersbourg, ix. 1874, p. 267; Mem. Acad. St. Petersbourg, 1889; T. Tschernyschew, Mem. Com. Geol. Russ. iii. 1889, No. 4.

265 W. Waagen, Mem. Geol. Surv. India, "Salt Range Fossils," vol. i. Productus Limestone, 1879–88.

Fusulina with Carboniferous brachiopods (Productus cora, P. semireticulatus, P. lineatus, Athyris Royssii, Spirifer striatus). The cephalopods are numerous and include the ammonoid types (Cyclolobus Arcestes, Medlicottia, Popanoceras, Xenodiscus), as well as many Nautili, Orthoceratites, and Gyroceratites. The gasteropods include forms of Bellerophon, Euomphalus, Holopella, Phasianella, and Pleurotomaria. Lamellibranchs are abundantly represented by such genera as Allorisma, Schizodus, Avicula, Aviculopecten, and Pecten, but also with others of a distinctly Mesozoic character, as Lima, Lucina, Loripes, Cardinia, Astarta, and Myophoria. Yet with these evidences of a newer facies of molluscan life it is interesting to notice the extraordinary variety and abundance of the brachiopods, including ancient genera such as Productus (20 species), Chonetes, Athyris, Orthis, Leptæna, and Streptorhynchus, mingled with a number of new genera first met with here (Hemiptychina, Notothyris, Lyttonia, Oldhamia, etc.). Though the general aspect of this fauna is so unlike that of the Permian rocks of central Europe, the appearance of a number of Zechstein species links the limestones of northern India with the European tract. Among these are Camarophoria humbletonensis, Strophalosia excavata, S. horrescens, Spiriferina cristata.

This oceanic type of deposit, however, does not seem to extend southward across the Indian peninsula. South of the line of the Narbada River a totally different series of sedimentary formations occurs. In that southern region the lower and middle Mesozoic marine rocks of other countries, and probably also the upper part of the Palæozoic series, are represented by a vast thickness of strata, chiefly sandstones and shales, which are probably almost entirely of fluviatile origin. To this great fresh-water accumulation the name of Gondwána system has been given by the Geological Survey of India. The lower parts of the system (Talchir and Damuda series) may perhaps be paralleled with the Permian rocks of Europe. The exceedingly coarse Talchir conglomerates contain blocks which sometimes show smoothed and striated faces, and have been compared with those of the bowlder-clay as evidences of ancient glacial action in India. Among the overlying sandstones and carbonaceous layers ferns (Gangamopteris, Glossopteris, Neuropteris) and Voltzia are found. The Damuda series, estimated to be 10,000 feet thick, contains Glossopteris, Gangamopteris, Schizoneura, Vertebraria, and Archegosaurus. The Panchet series

which succeeds is more probably Triassic, while the upper subdivisions appear to be of Jurassic age.[266]

Australia.—The "Upper Coal-measures" (Newcastle series) of New South Wales have been classed as Permian. They consist of shales, sandstones, and conglomerates, with abundant plant-remains (Glossopteris, Gangamopteris, Vertebraria, Phyllotheca, Sphenopteris), but with no marine shells. This group of coal-bearing strata comprises nearly all the seams of coal in the Newcastle coal-field, the lowest of which is from eight to fifteen feet thick. Another seam, near Jamberoo, is twenty-five feet thick.[267]

In Victoria certain sandstones and conglomerates (Bacchus Marsh, Grampian) have been compared with those of the Talchir series of India as possibly indicating glacial action. They contain Gangamopteris and Glossopteris.[268] In Queensland a much fuller development of Upper Palæozoic rocks has been ascertained. A great thickness of stratified deposits comprising four or five distinct formations has been named Permo-Carboniferous. In its higher portions (Bowen series) it consists of an upper fresh-water series with plants (Sphenopteris, Glossopteris), and a lower marine series containing a fauna which includes the genera Fenestella, Dielasma, Spirifer (striatus, trigonalis, etc.), Derbyia, Productus (cora, etc.), Strophalosia, Chonetes, Aviculopecten, Platyschisma, Mourlonia, Bellerophon, Porcellia, Orthoceras, Goniatites.[269]

Africa.—In the south of this continent a group of rocks occurs which presents some of the lithological and palæontological types of southern India and southeastern Australia. At their base is a remarkable conglomerate (Dwyka) which lies unconformably on the Carboniferous quartzite and has been compared with the conglomerate of the Talchir series, but it presents many of the characters of a volcanic conglomerate.[270] It is surmounted by a series of clays or mudstones and sandstones, at least 4000 feet thick, con-

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266 Medlicott and Blanford, "Geology of India."

267 C. S. Wilkinson, "Notes on Geology of New South Wales," Sydney, 1882, p. 51. O. Feistmantel, Mem. Geol. Surv. N.S. Wales, Palæontology, No. 3, 1890, p. 38.

268 R. A. F. Murray, "Geology and Phys. Geog. of Victoria," 1887, p. 84.

269 R. L. Jack and R. Etheridge jun. "Geology and Palæontology of Queensland and New Guinea," 1892, chaps. vi.–xxii.

270 A. H. Green, Quart. Journ. Geol. Soc. xliv. 1888, p. 239.

taining plant-remains, among which Glossopteris is said to have been recognized. This series is unconformably surmounted by the "Kimberley shales," which pass up into the "Karoo beds." The latter are generally regarded as Triassic.

North America.—The Permian system is hardly represented at all in this part of the globe. In Kansas certain red and green clays, sandstones, limestones, conglomerates, and beds of gypsum lie conformably on the Carboniferous system, and contain a few genera and species of mollusks (Bakevellia, Myalina, etc.) which occur in the European Permian rocks. It has been urged, however, that the upper part of the Appalachian coal-field should be regarded as belonging to the Permian system. These strata, termed the "Upper Barren Measures," are upward of 1000 feet thick. At their base lies a massive conglomeratic sandstone, above which come sandstones, shales, and limestones, with thin coals, the whole becoming very red toward the top. Professors W. M. Fontaine and I. C. White have shown that, out of 107 plants examined by them from these strata, 22 are common to the true Pennsylvanian Coal-measures and 28 to the Permian rocks of Europe; that even where the species are distinct they are closely allied to known Permian forms; that the ordinary Coal-measure flora is but poorly represented in the "Barren Measures," while on the other hand vegetable types appear of a distinctly later time, forms of Pecopteris, Callipteridium, and Saportæa foreshadowing characteristic plants of the Jurassic period. These authors likewise point to the indications furnished by the strata themselves of important changes in the physical condition of the American area, and to the remarkable paucity of animal life in these beds, as in the red Permian rocks of Europe. The evidence at present before us seems certainly in favor of regarding the upper part of the Appalachian coal-fields as representing the reptiliferous beds overlying the Coal-measures at Autun and their equivalents.[271] In Nova Scotia also a similar upward passage has been observed from true Coal-measures into a group of reddish strata containing Permian types of vegetation.

Passing to the western regions of the continent, we find

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[271] "On the Permian or Upper Carboniferous Flora of W. Virginia and S.W. Pennsylvania," Second Geol. Surv. Penn. Report, P.P., 1880.

that the vegetation which succeeded that of the Carboniferous period spread far to the west, and that it has been entombed among marine sediments. The Permian deposits traced in that direction undergo a change somewhat similar to that shown by the Carboniferous system, though on a much feebler scale. In the so-called "Wichita beds" of Texas, consisting of red and mottled clays, sandstones and concretionary limestones resting on Coal-measures, a series of plant and animal remains has been discovered, which throws much light upon the extension of the Permian flora and fauna in North America. The plants are essentially the same as those found above the Coal-measures of Western Virginia. They include Sphenophyllum, Annularia, Walchia, Odontopteris, Callipteris conferta, Callipteridium (4 species), Pecopteris (8 species), and Goniopteris.[272] The animal-remains comprise some Carboniferous species, but also distinctively Permian types, especially some of the ammonoid cephalopods, which are now known to have so wide a range in the Old World. The cephalopods already obtained include species of Orthoceras, Nautilus, Waagenoceras, Medlicottia, Popanoceras, the gasteropods are represented by species of Euomphalus, Bellerophon, and Murchisonia, and other organisms have been detected.[273] There have also been obtained from those strata and the "Clepsydrops shales" of Illinois a number of fish, stegocephalous amphibia, and rhynchocephalous reptiles.[274]

Spitzbergen.—The Permian sea appears to have extended far within the Arctic Circle, for above the Carboniferous rocks of Spitzbergen there occurs a group of strata which contains Permian forms (Productus, Streptorhynchus, Retzia, Pseudomonotis, Bakevellia, etc.).[275]

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[272] I. C. White, Bull. Amer. Geol. Soc. iii. 1892, p. 217.

[273] C. A. White, Amer. Nat. 1889, p. 109, Bull. U. S. Geol. Surv. No. 77, 1891.

[274] E. D. Cope, Proc. Amer. Phil. Soc. xvii. 1877–78, pp. 182, 505.

[275] B. Lundgren, Bihang. Svensk. Vet. Akad. Handl. xiii. 1887.

END OF THIRD PART OF "TEXT-BOOK OF GEOLOGY"